

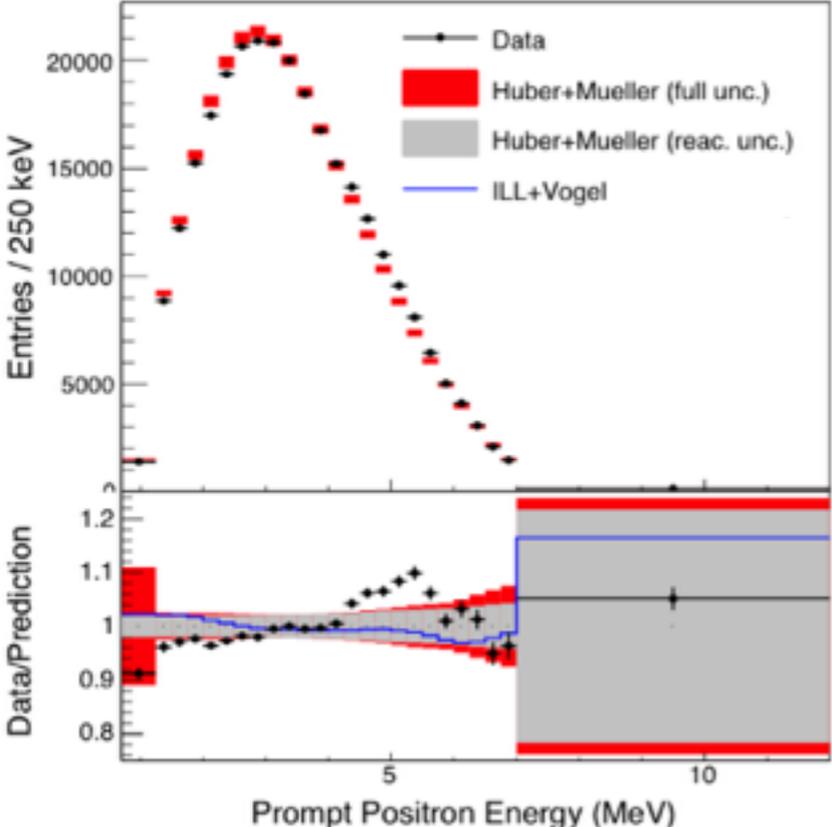
# Precision Reactor $\bar{\nu}_e$ Spectrum Measurements: Recent Results and PROSPECTs

November 11, 2015

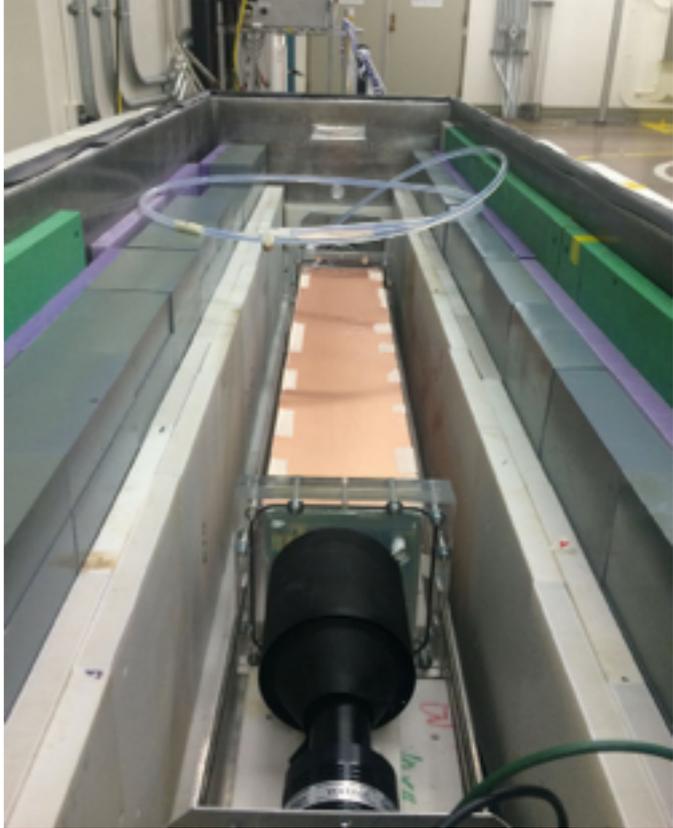
Bryce Littlejohn  
Illinois Institute of Technology



Daya Bay Antineutrino Spectrum



PROSPECT20 Prototype at HFIR



PROSPECT20 Prototype in Shield at HFIR



# Outline

---

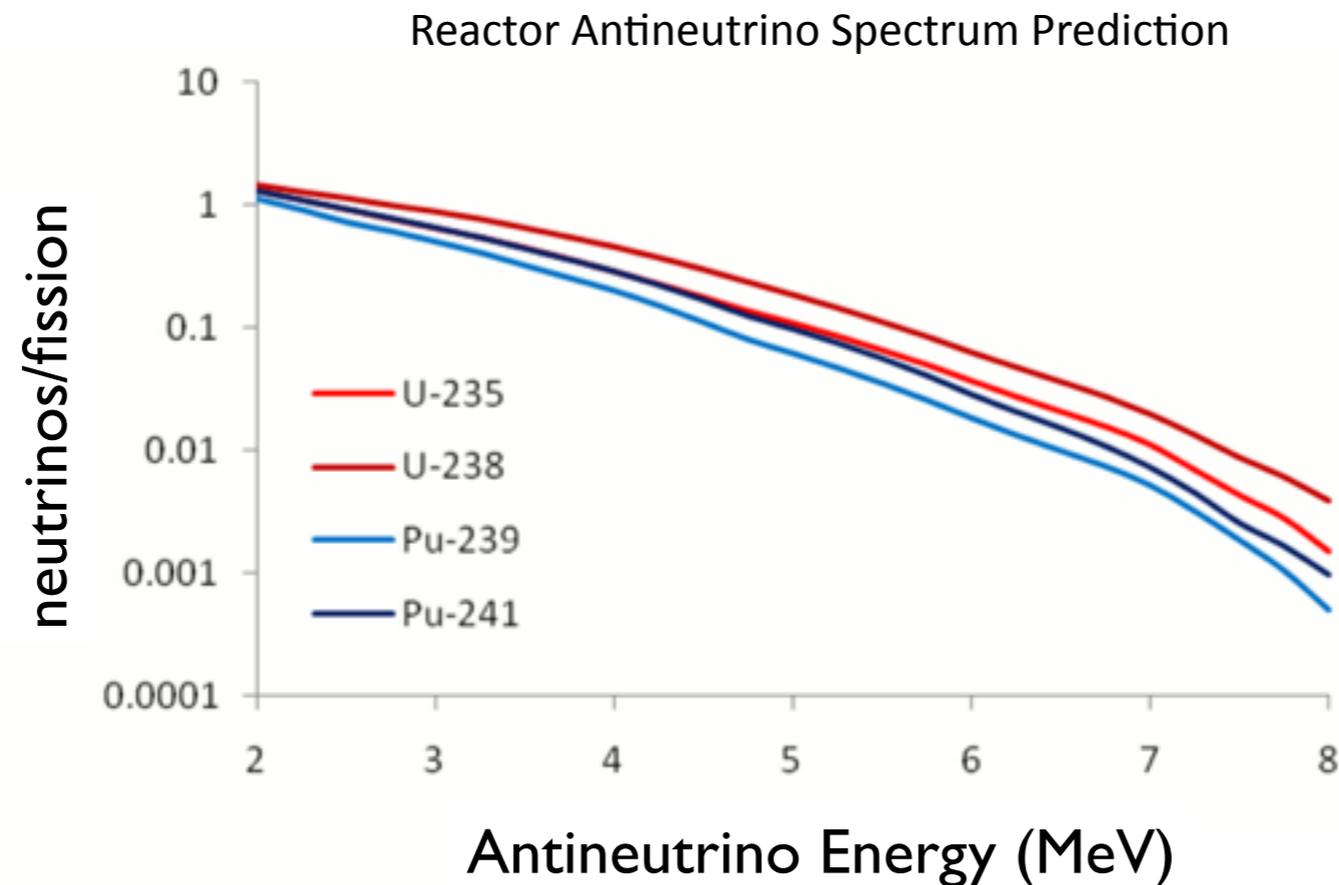


- Intro: Reactor  $\bar{\nu}_e$  Flux and Spectrum Predictions
- Reactor Anomaly and recent flux/spectrum measurements
- Measurement of the  $\bar{\nu}_e$  spectrum at PROSPECT
- Current context for PROSPECT

# Outline



- Intro: Reactor  $\bar{\nu}_e$  Flux and Spectrum Predictions
- Reactor Anomaly and recent flux/spectrum measurements
- Measurement of the  $\bar{\nu}_e$  spectrum at PROSPECT
- Current context for PROSPECT



# Reactor Neutrino History

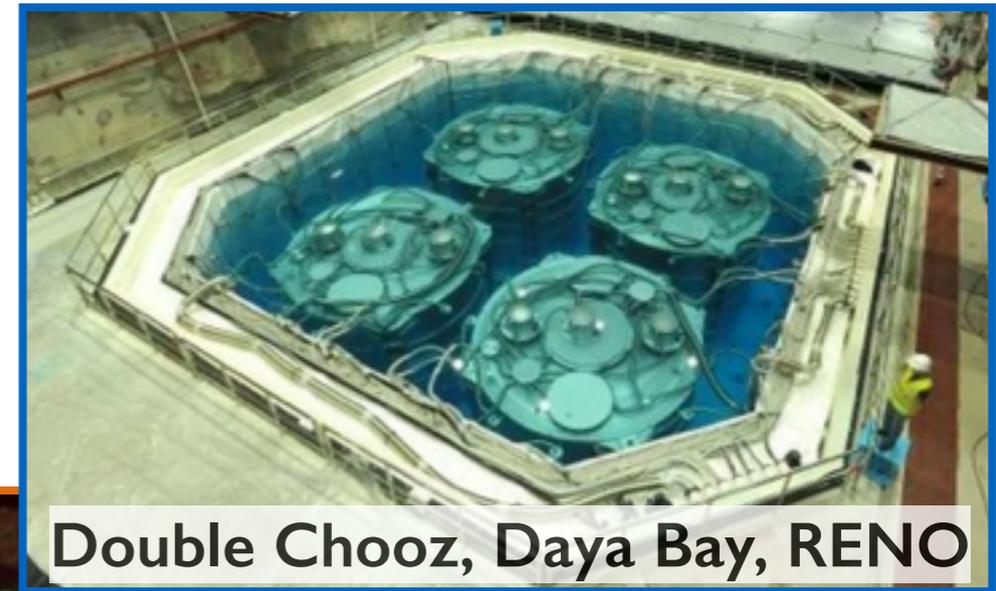


- Reactor  $\bar{\nu}_e$ : a history of discovery  
Many experiments, differing baselines

1970s-80s-90s:

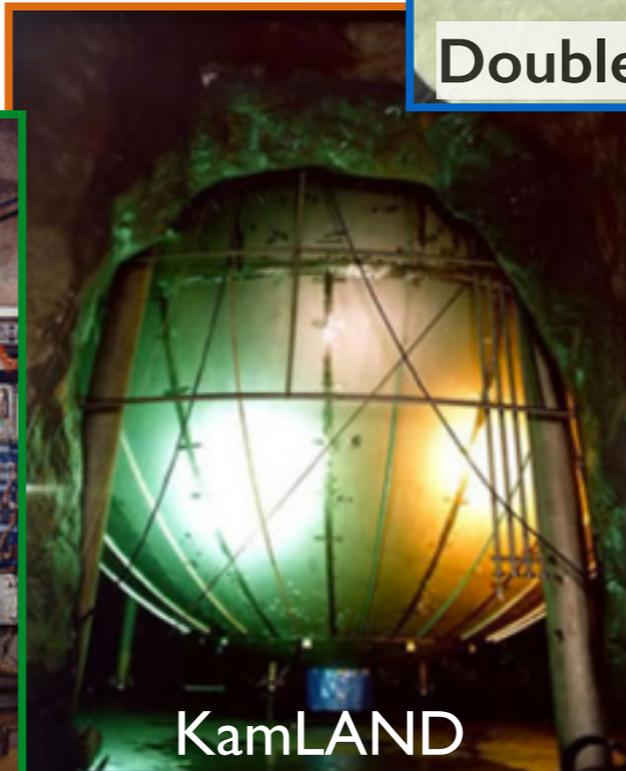
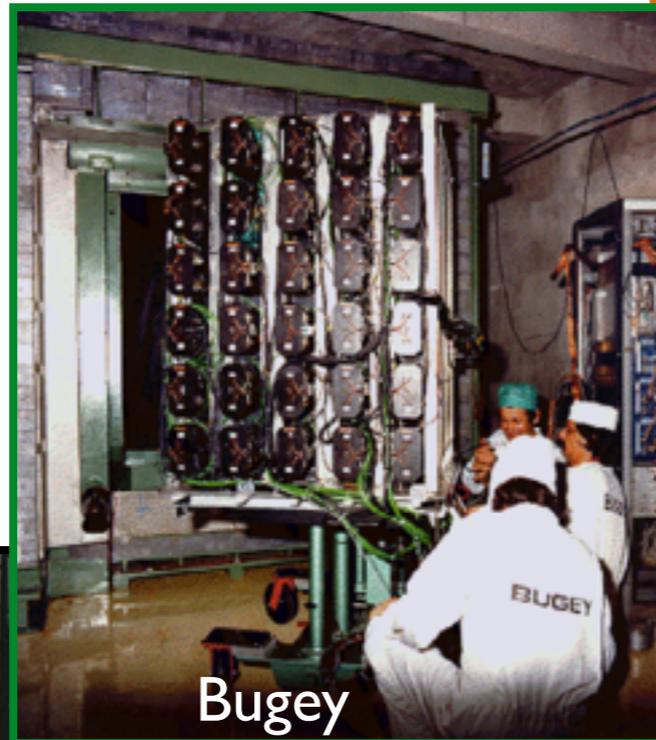
Reactor flux,

Cross-section measurements



2010s:  
 $\theta_{13}$ , precision  
oscillation  
measurements

1950s: First  
neutrino  
observation



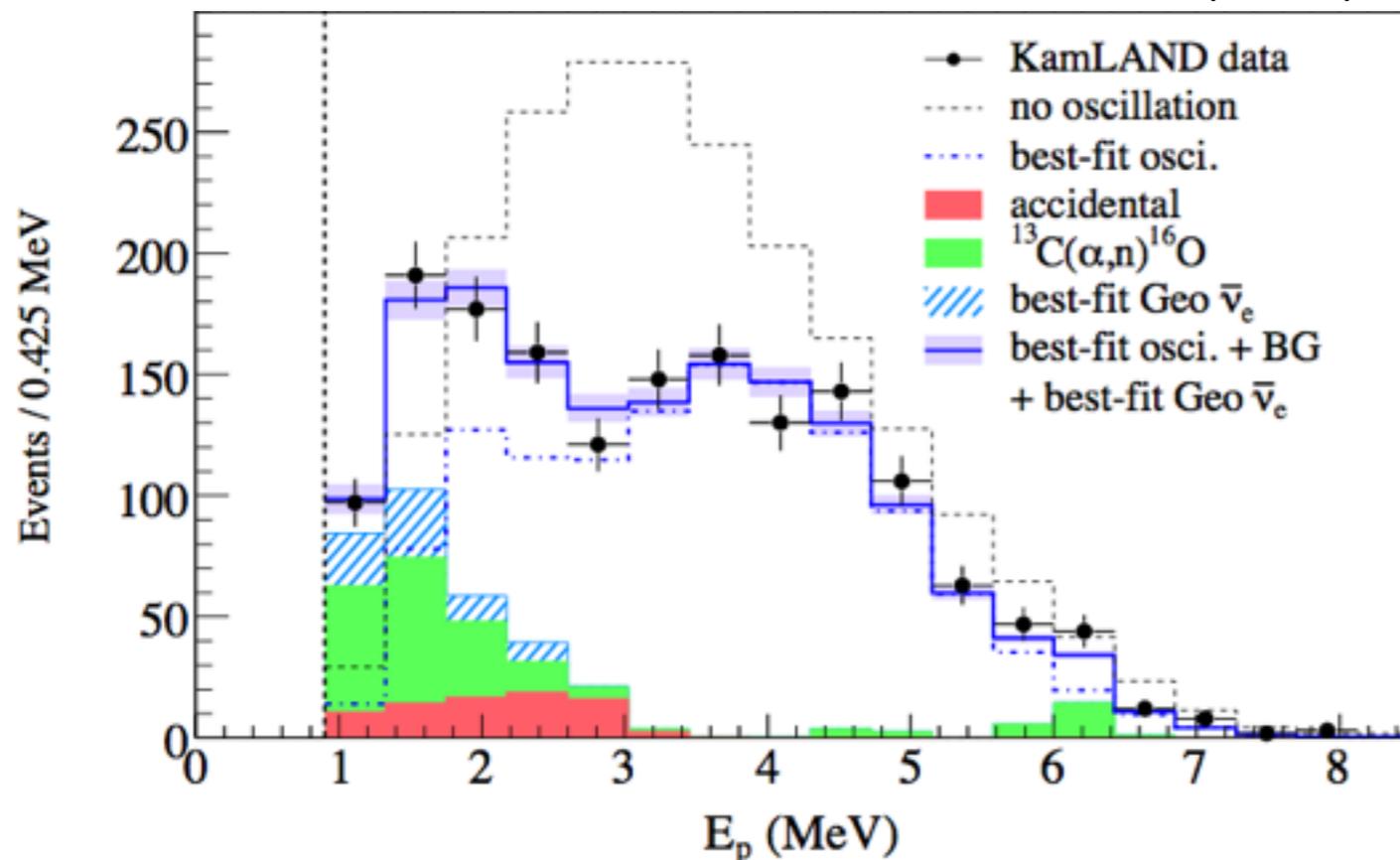
2000s:  $\bar{\nu}_e$  disappearance,  
 $\bar{\nu}_e$  oscillation measurements

# Reactor Neutrino Discovery

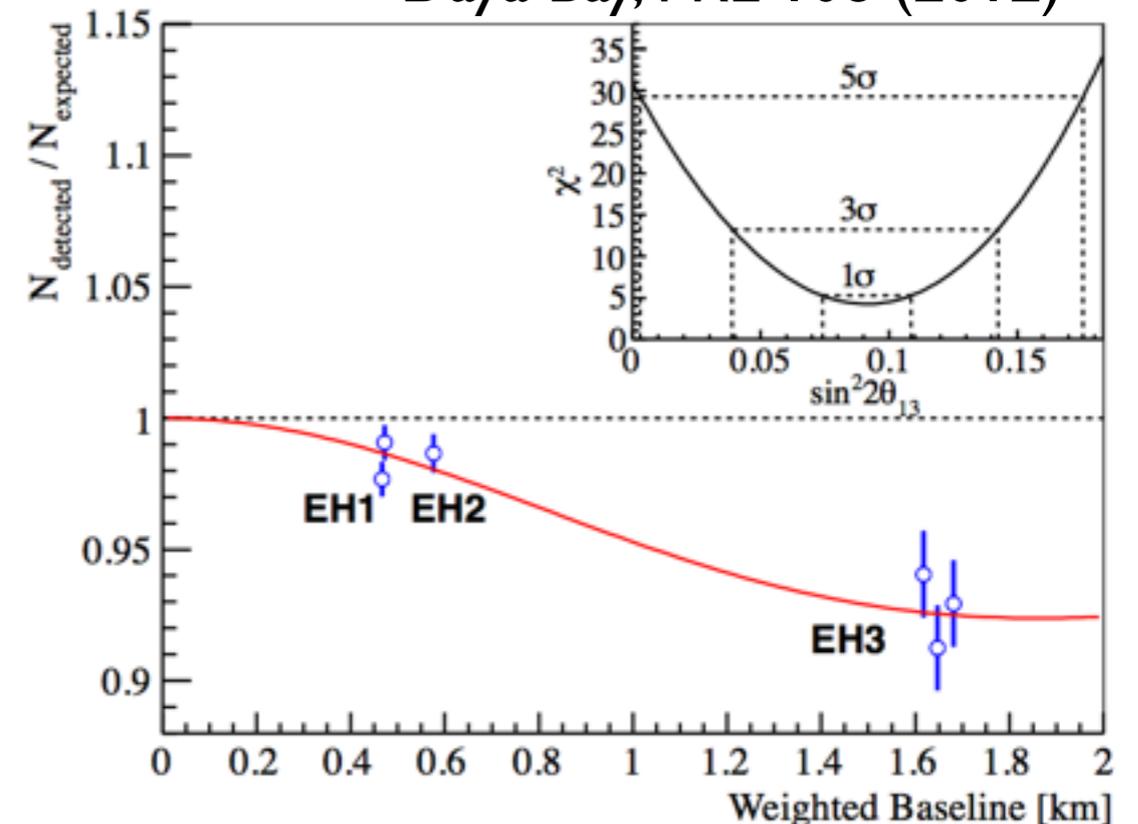


- How are these discoveries made?
- Comparing observed reactor neutrinos at different sites
- Comparing observed reactor neutrinos to predictions based on some model of how nuclear reactors work

KamLAND, PRL 100 (2008)



Daya Bay, PRL 108 (2012)



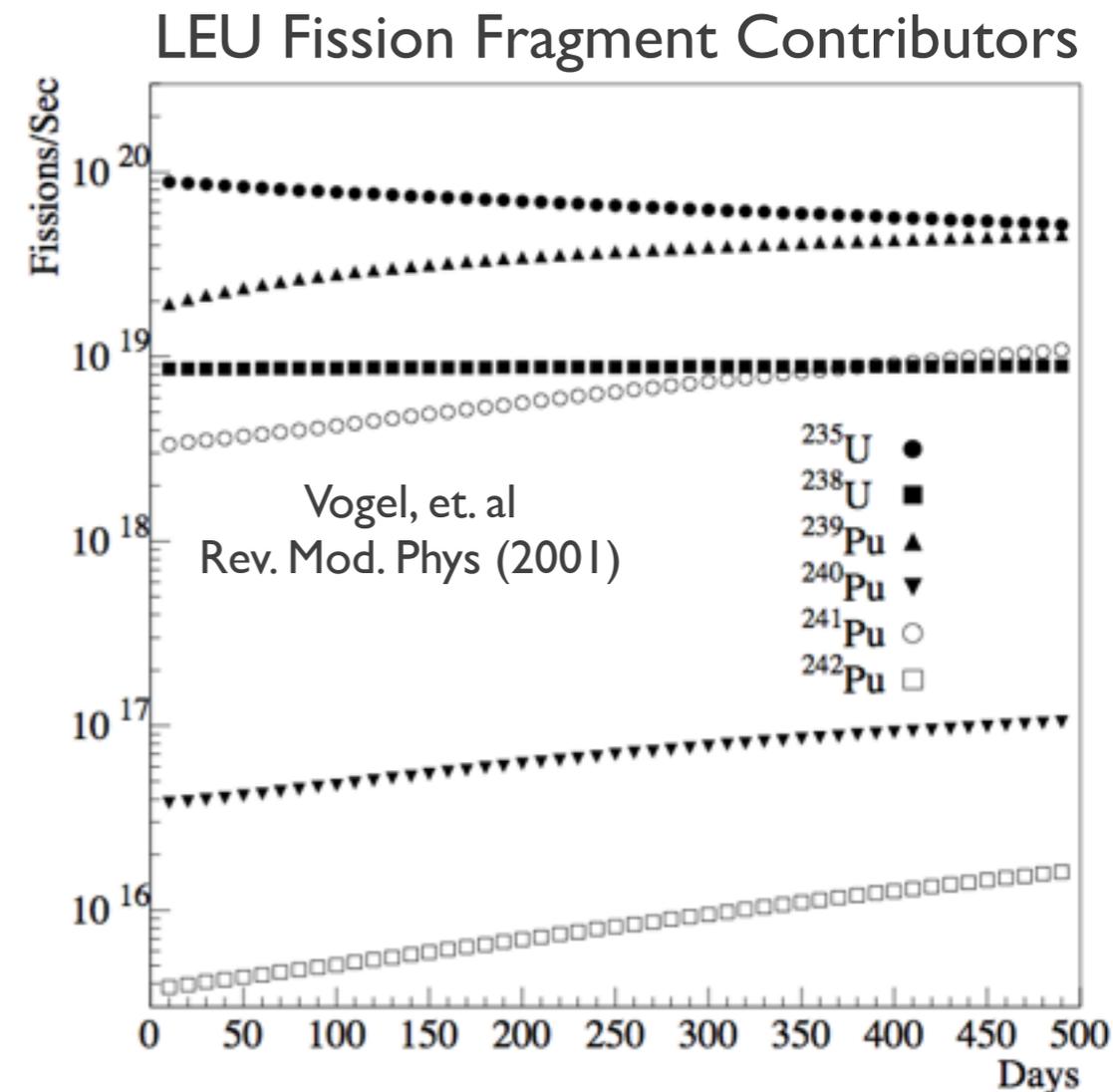
2000s:  $\bar{\nu}_e$  disappearance,  
 $\bar{\nu}_e$  oscillation measurements

2010s:  $\theta_{13}$ , precision  
oscillation measurements

# Reactor Antineutrino Production



- Fission isotopes fission, creating neutron-rich daughters
  - Low-enriched (LEU): Many fission isotopes
  - Highly-enriched (HEU): U-235 fission only
- Overall fission rate described largely by reactor thermal power

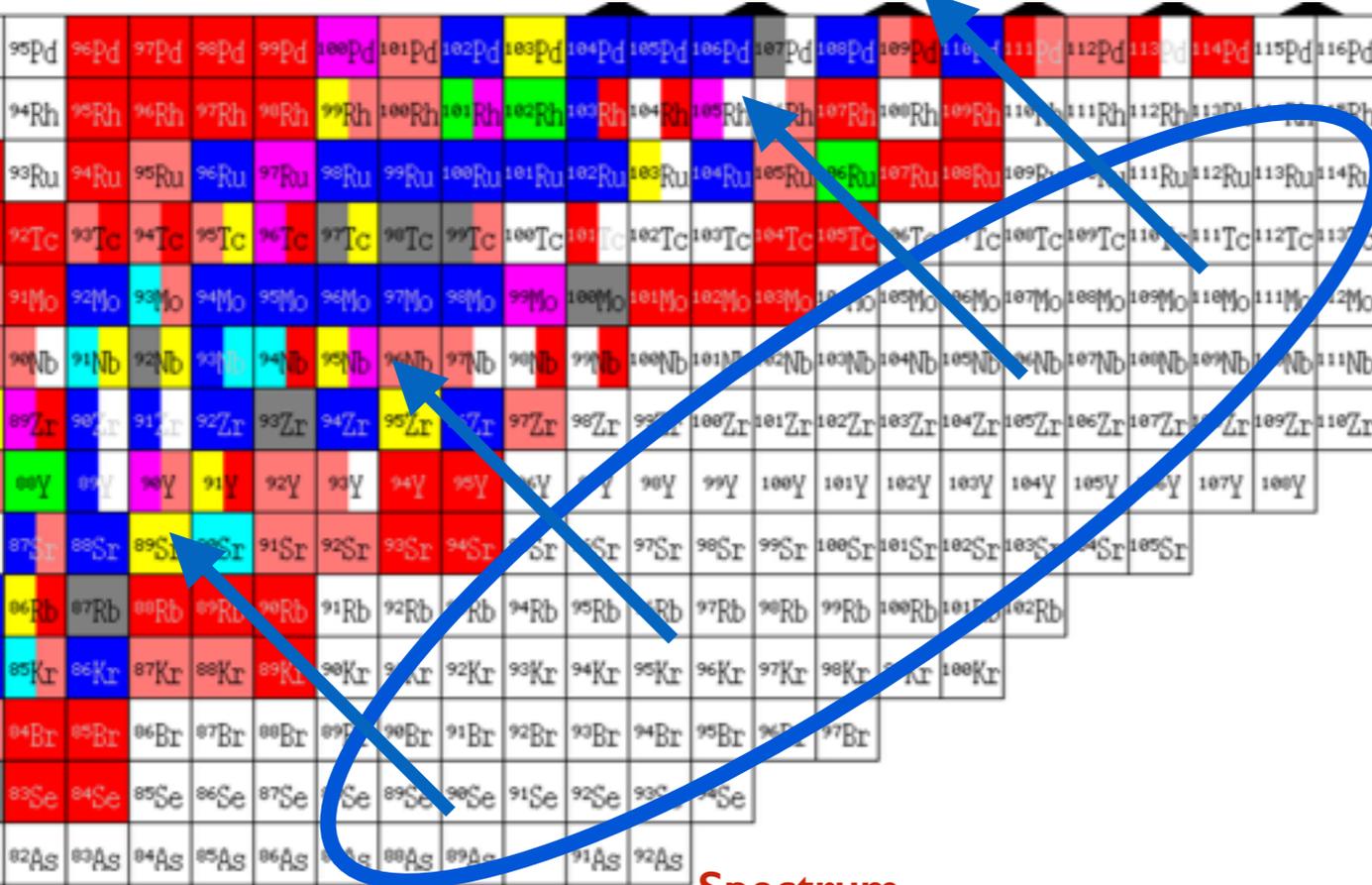
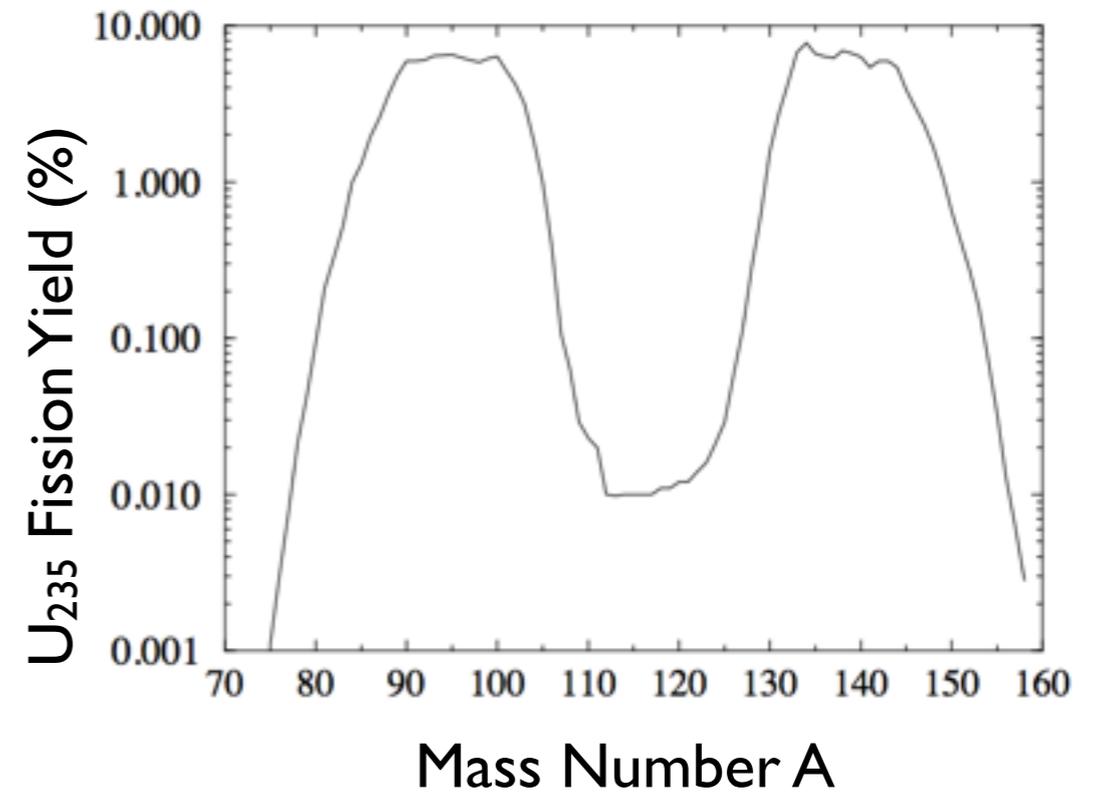
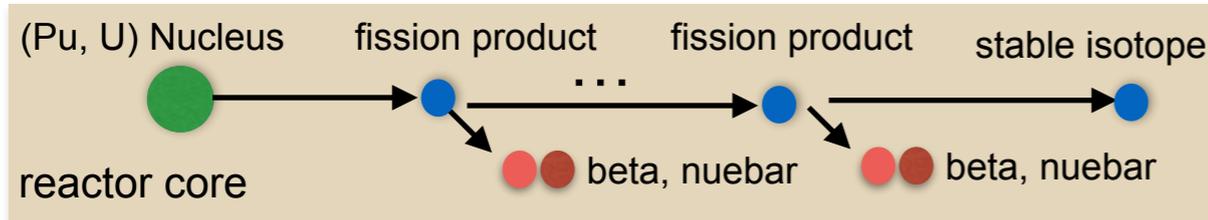




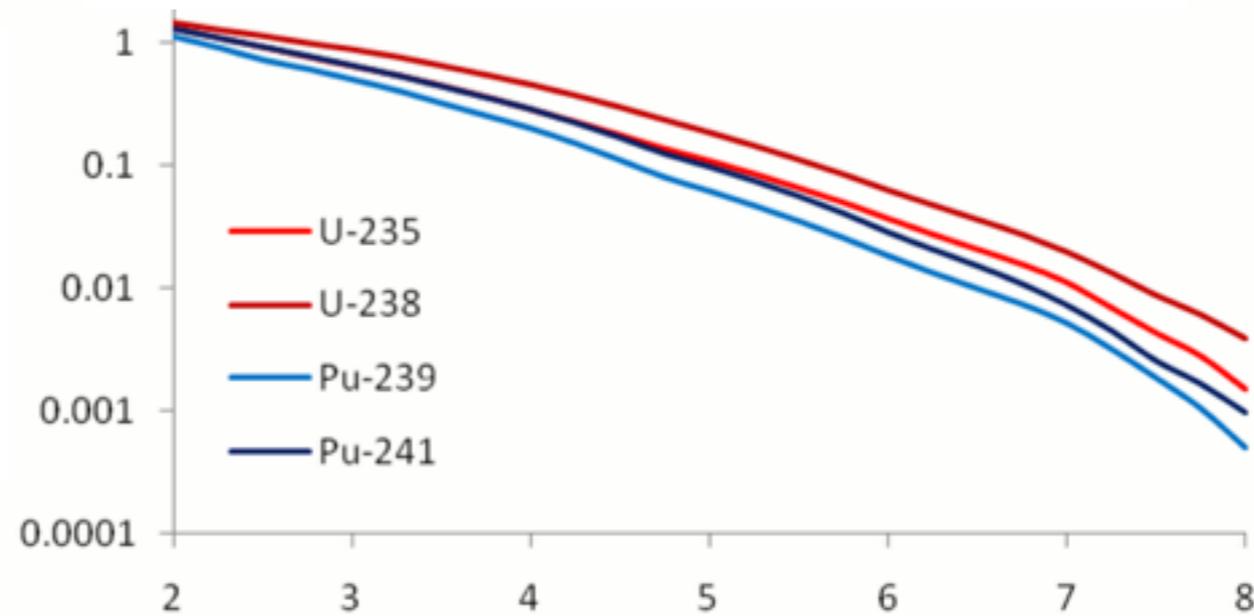
# Reactor Antineutrino Production

- Reactor  $\bar{\nu}_e$ : produced in decay of product beta branches

- Each isotope: different branches, so different neutrino energies (slightly)



neutrinos/fission



Antineutrino Energy (MeV) 7

$$S(E) = \sum_i F_i S_i(E) \quad F_i = \frac{W_{th} f_i}{\sum_k f_k E_k}$$

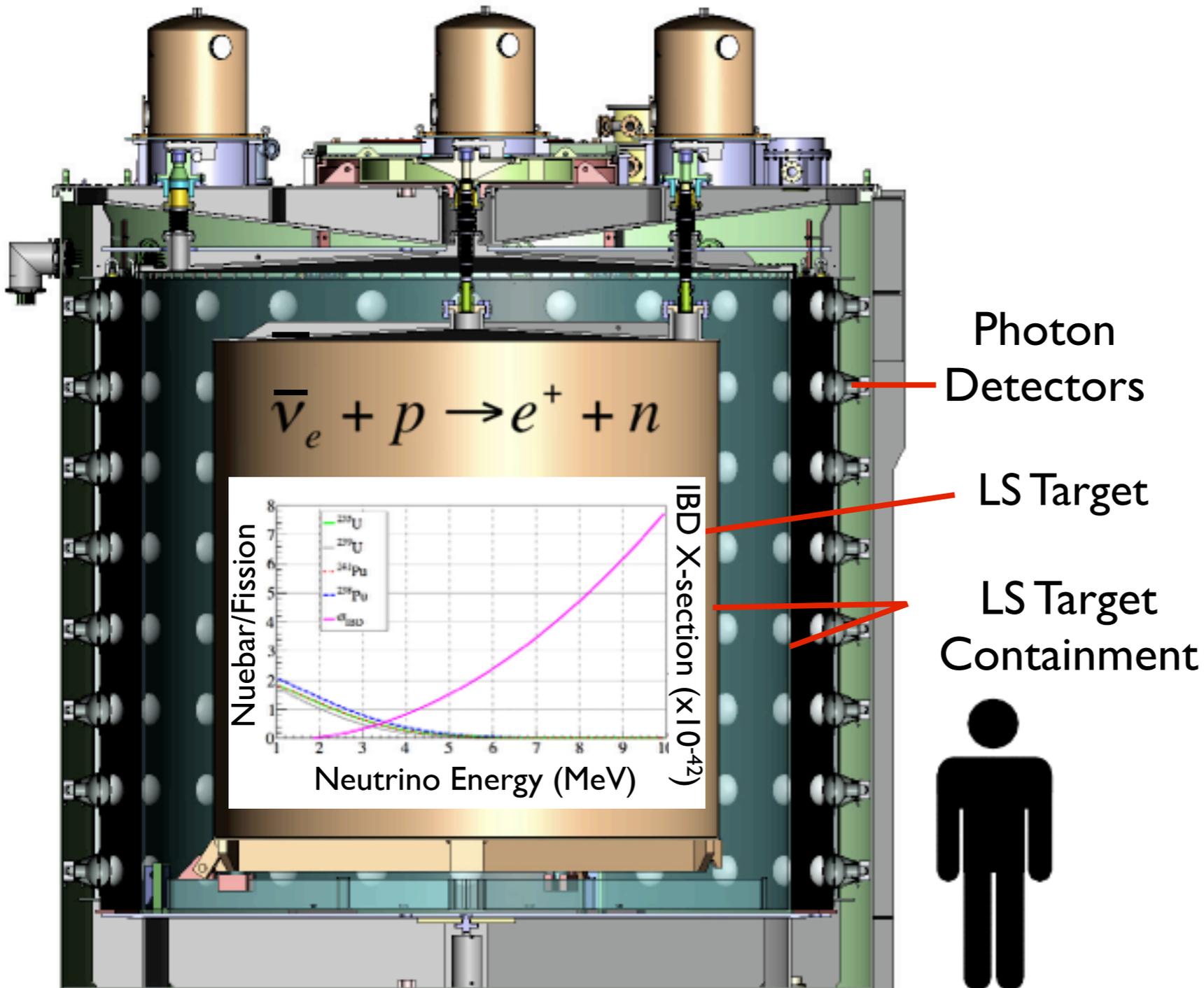
Fission Isotope  $i$  Flux

Spectrum

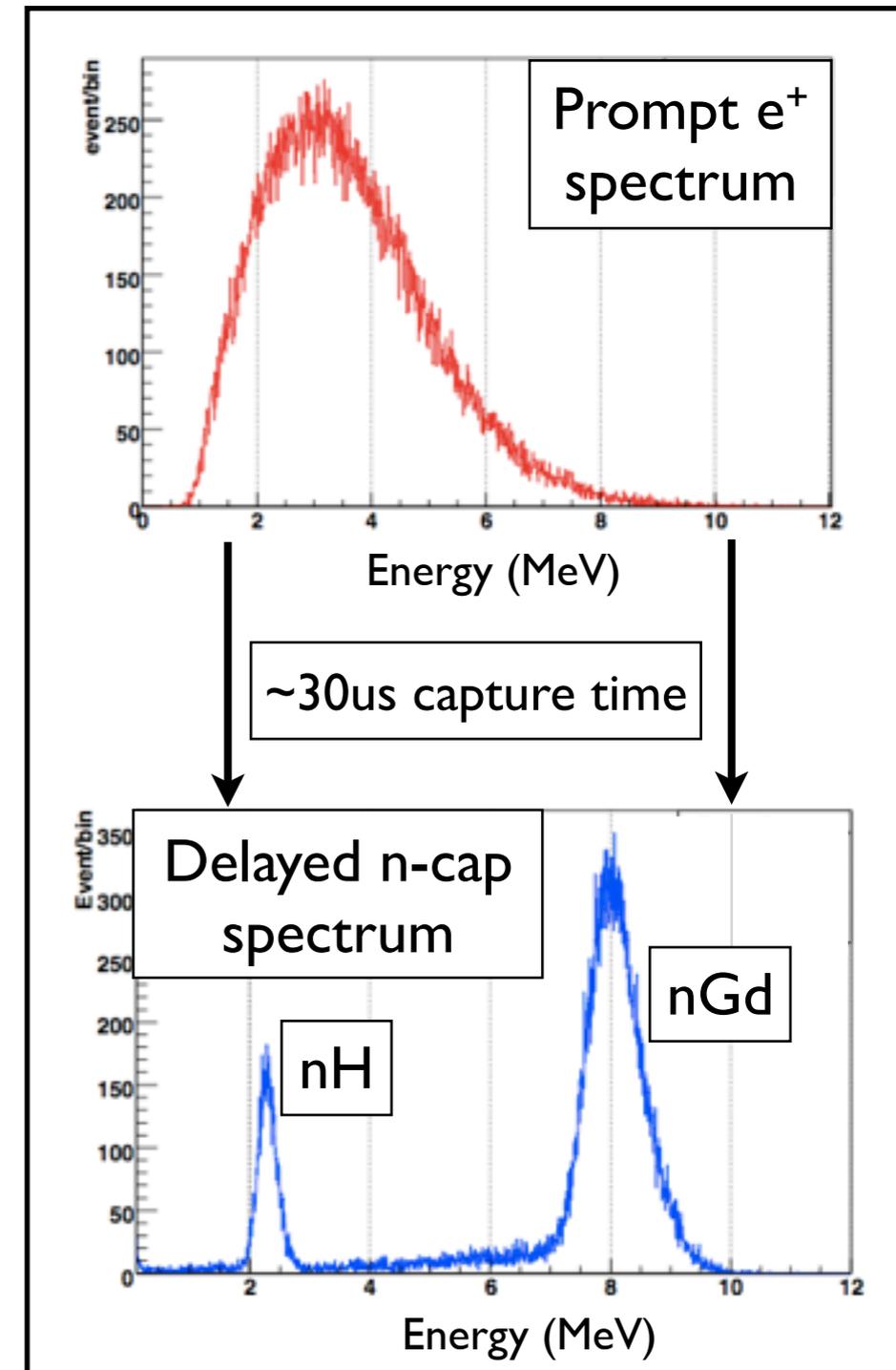
# Reactor Antineutrino Detection



- Detect inverse beta decay with liquid or solid scintillator, PMTs
- IBD  $e^+$  is direct proxy for antineutrino energy



Example: Daya Bay Detector



Daya Bay Monte Carlo Data

# Predicting $S_i(E)$ , Neutrinos Per Fission



- Two main methods:

- *Ab Initio* approach:

- Calculate spectrum branch-by-branch using beta branch databases: endpoints, decay schemes
- **Problem:** many rare beta branches with little information; infer these additions

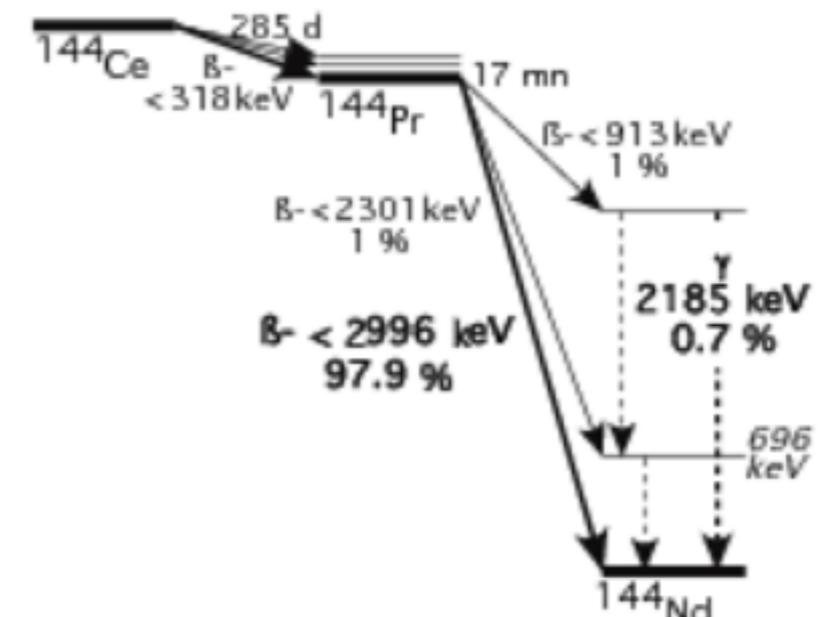
- Conversion approach

- Measure beta spectra directly
- Convert to  $\bar{\nu}_e$  using 'virtual beta branches'
- **Problem:** 'Virtual' spectra not well-defined: what forbiddenness, charge, etc. should they have?
- Devised in 50's, each method has lost and gained favor over the years

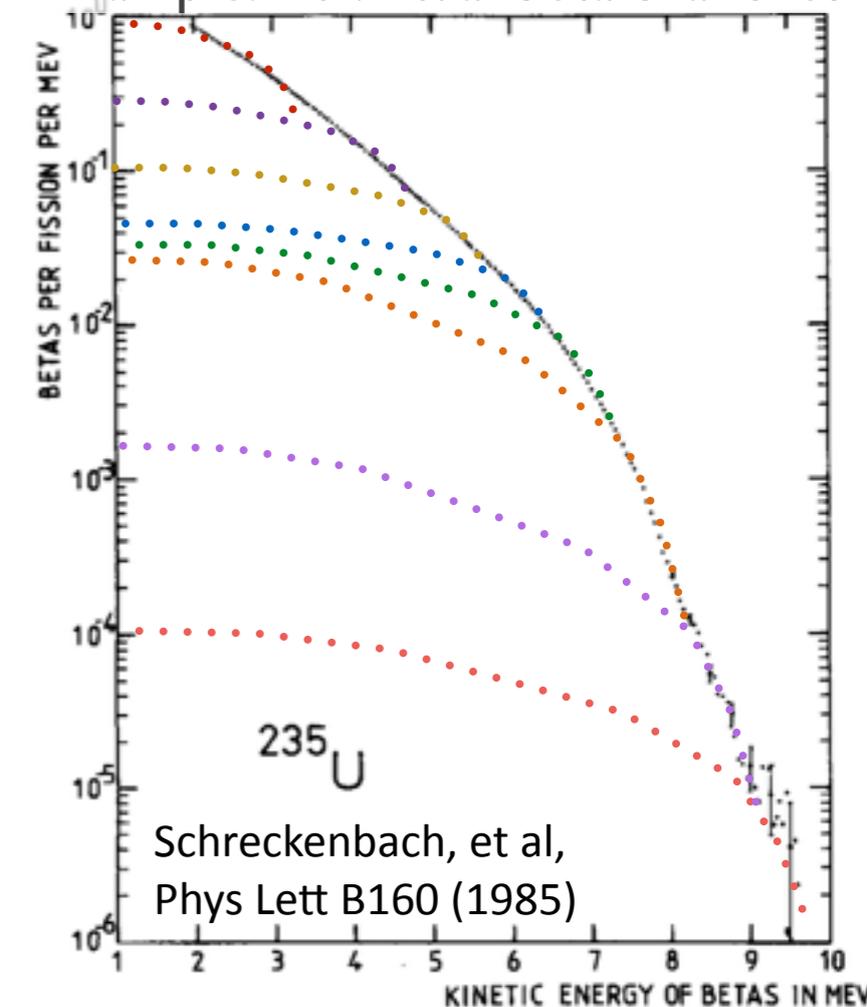
Carter, *et al*, Phys. Rev. 113 (1959)

King and Perkins, Phys. Rev. 113 (1958)

Example: Ce-144 Decay Scheme



Example: Fit virtual beta branches



# Predicting $S_i(E)$ , Neutrinos Per Fission



- Early 80s: ILL  $\bar{\nu}_e$  data fits newest *ab initio* spectra well

Davis, Vogel, et al., PRC 24 (1979)

Kown, et al., PRD 24 (1981)

- 1980s: New reactor beta spectra: measurements — conversion now provides lower systematics

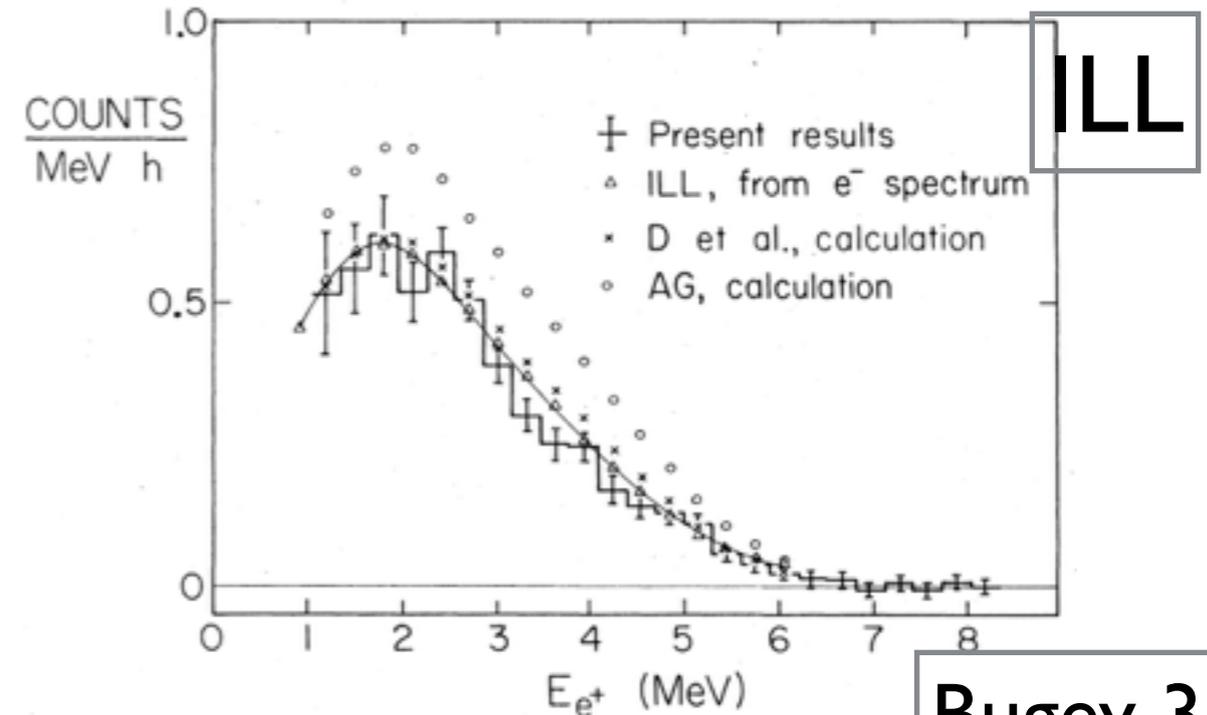
Schreckenbach, et al., Phys Lett B160 (1985)

Schreckenbach, et al., Phys Lett B218 (1989)

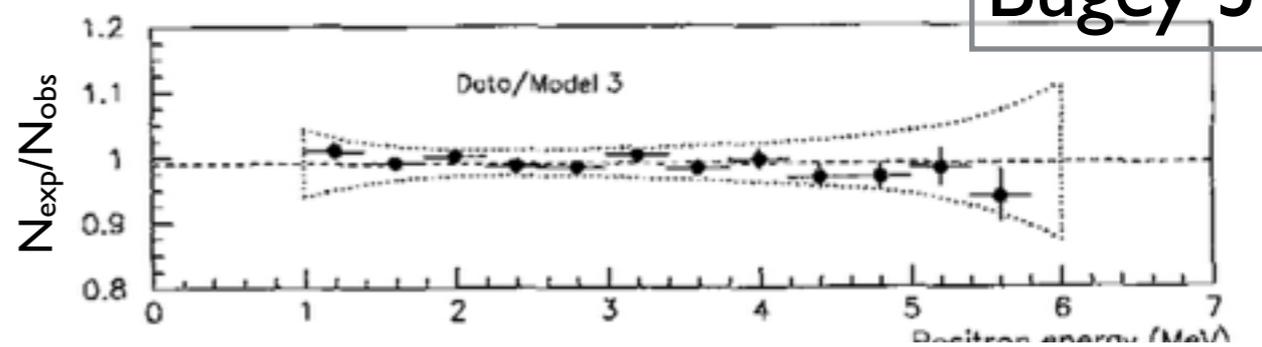
- 1990s: Bugey measurements fit converted spectrum well

B. Achkar, et al., Phys Lett B374 (1996)

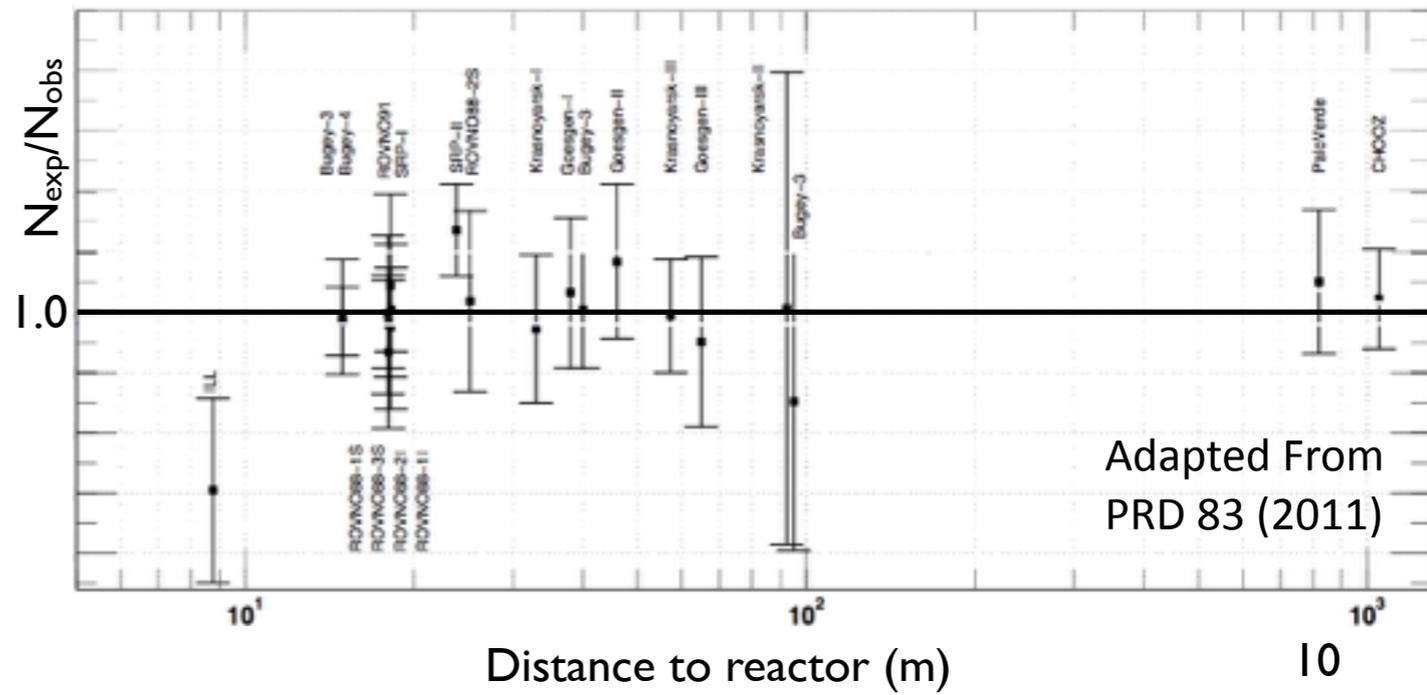
- 1980s-2000s: Predicted, measured fluxes agree



ILL



Bugey 3



Adapted From PRD 83 (2011)

# Recent History: Problems Emerge



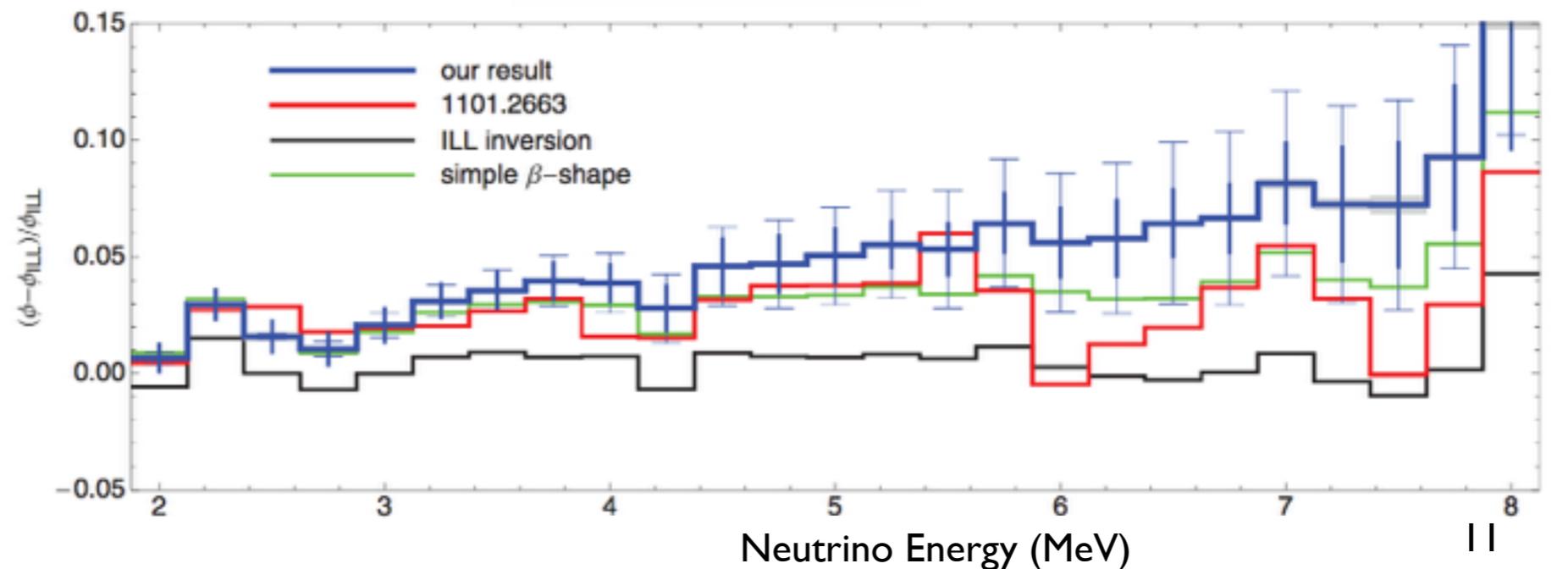
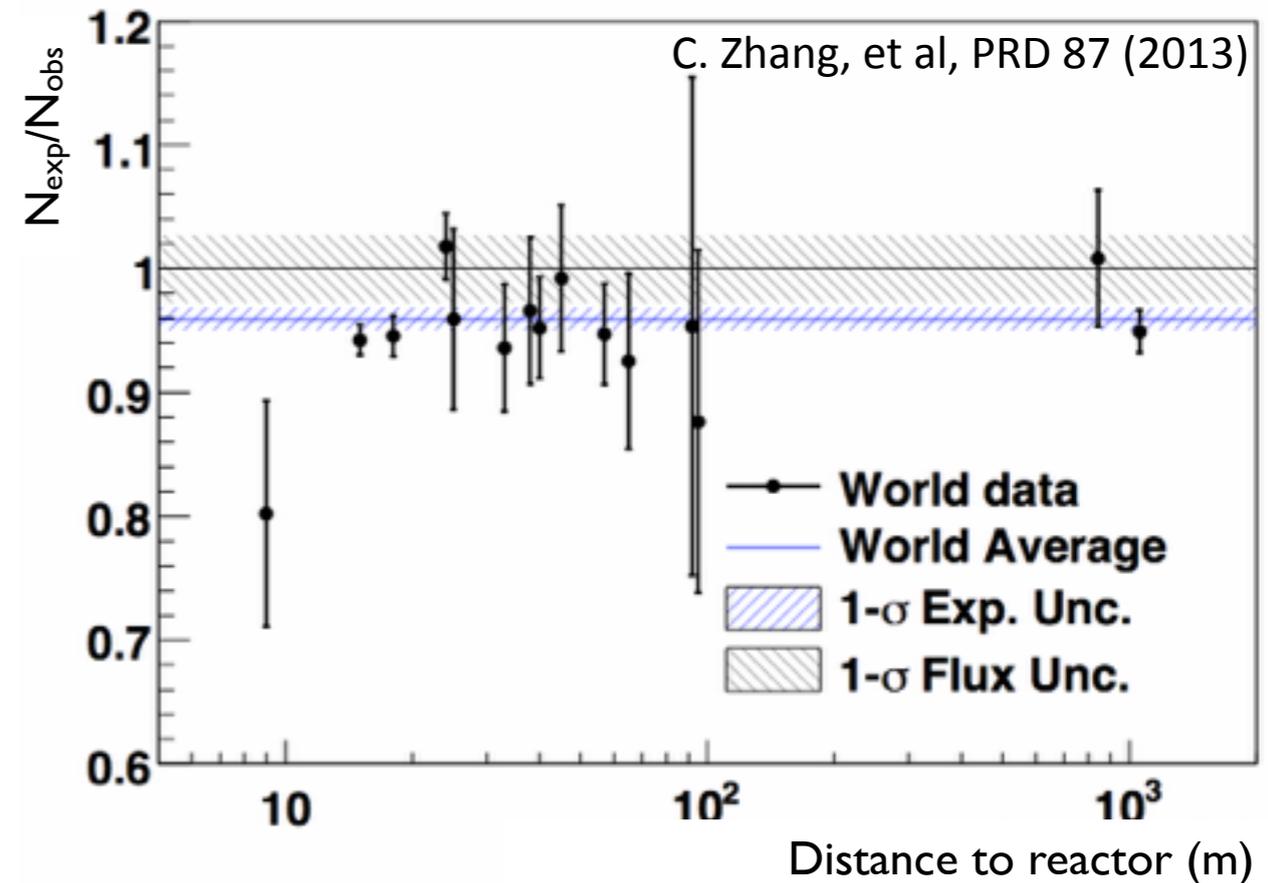
- 2010s: Re-calculation of conversion for  $\theta_{13}$  measurements

- Start with ab initio approach
- Subtract this from ILL beta spectra
- Use conversion procedure on remaining beta spectrum:  $\sim 10\%$
- OR Huber: virtual branches only

- **Change in flux/spectrum!**

- Flux increase from:
  - Conversion ( $\sim 3\%$ )
  - X-section (1%)
  - Non-equilibrium isotopes (1%)

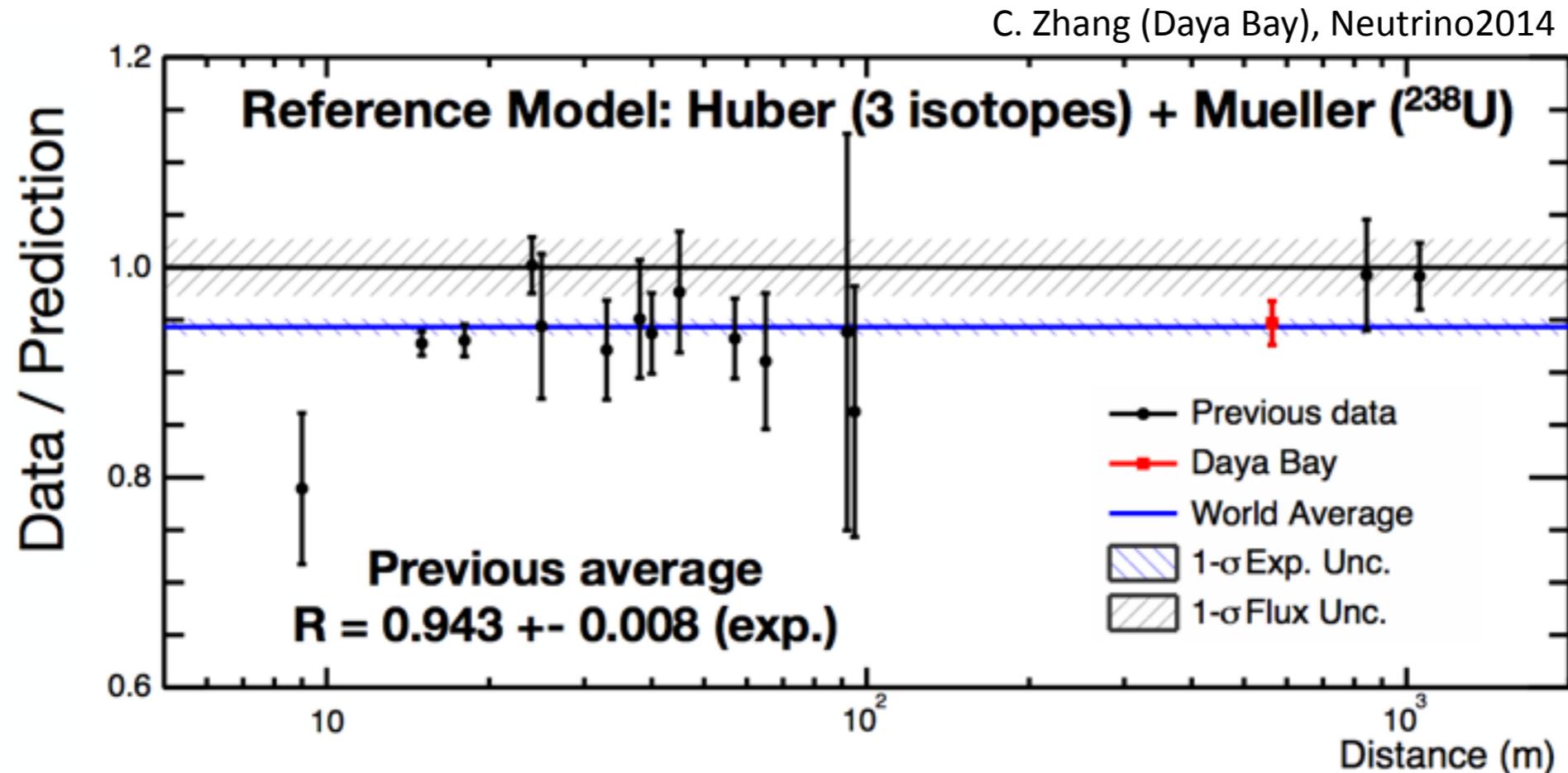
Mueller, *et al*, Phys. Rev. C83 (2011)  
 Mention, *et al*, Phys. Rev. D83 (2011)  
 Huber, Phys. Rev. C84 (2011)



# Outline



- Intro: Reactor  $\bar{\nu}_e$  Flux and Spectrum Predictions
- **Reactor Anomaly and recent flux/spectrum measurements**
- Measurement of the  $\bar{\nu}_e$  spectrum at PROSPECT
- Current context for PROSPECT

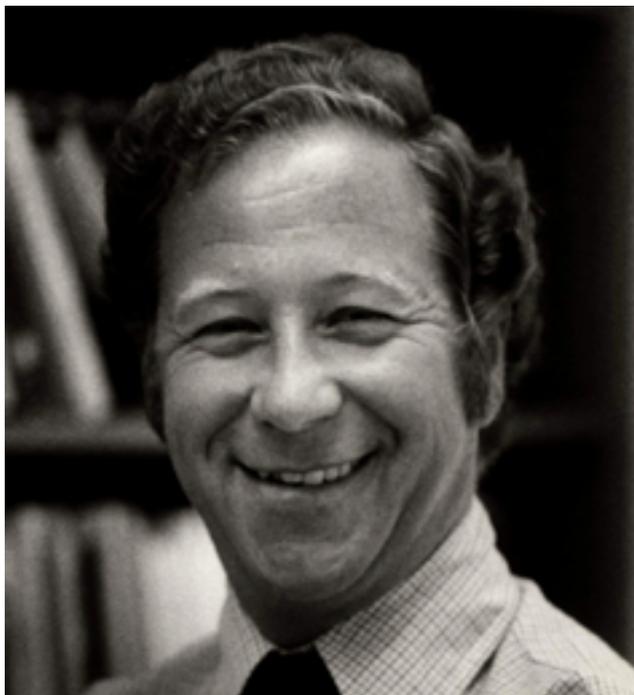
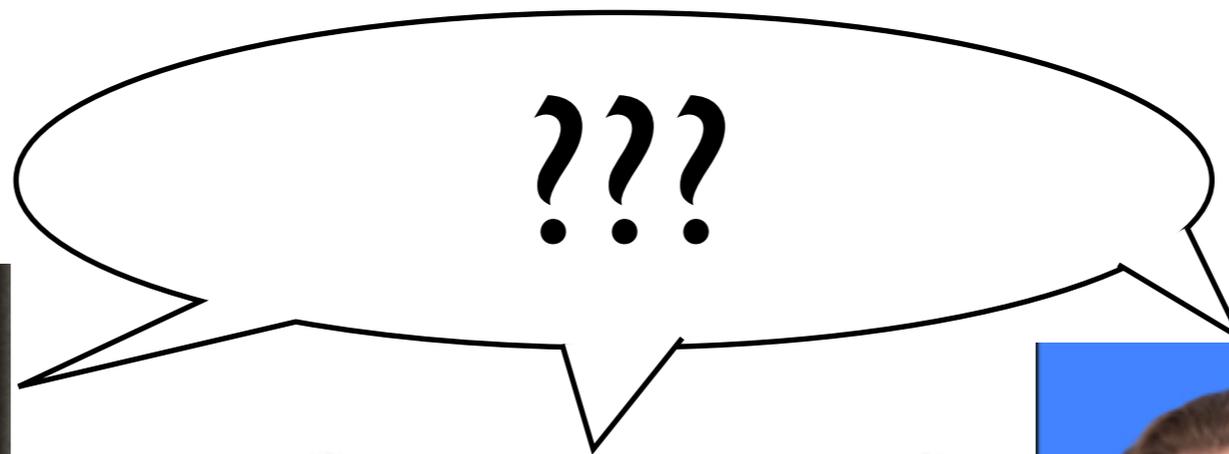


# Reactor Antineutrino Anomaly?

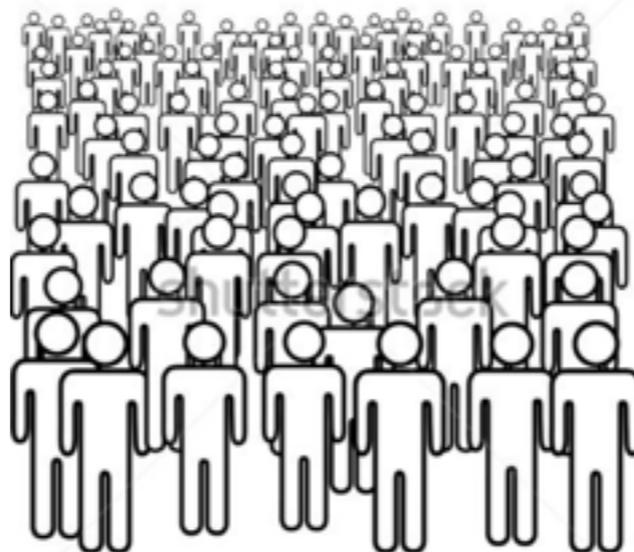


- Do we have a ‘reactor antineutrino anomaly?’

- “No: the previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time.”
- “Yes: but probably attributable to uncertainties in the beta-to- $\nu_e$  conversion.”
- “Yes: the deficit could result from short-baseline sterile neutrino oscillations.”



P. Vogel, Caltech



The rest of us



T. Lasserre,  
CEA, France



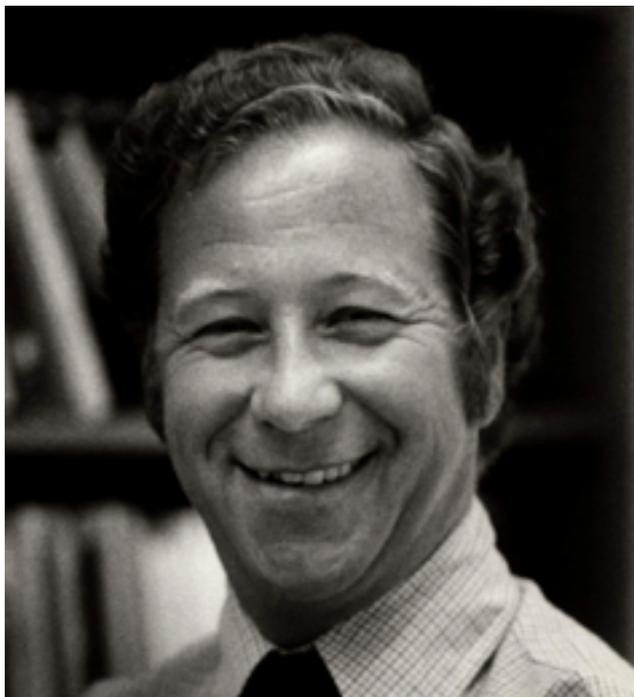
P. Huber,  
VTech

# Reactor Antineutrino Anomaly?

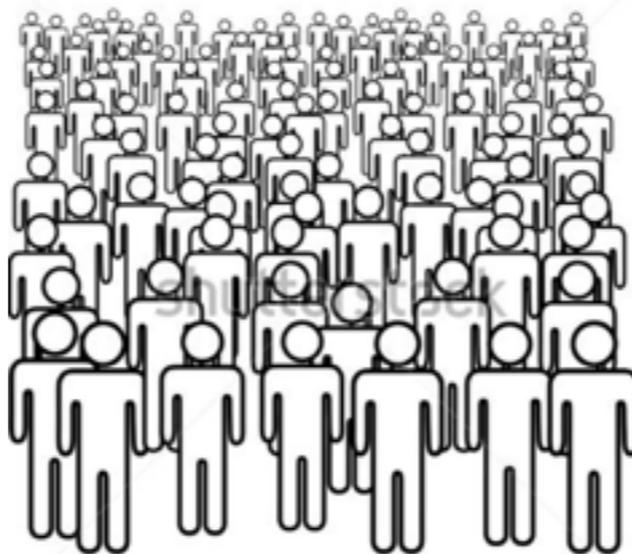


- Do we have a ‘reactor antineutrino anomaly?’
  - “No: the previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time.”
  - “Yes: but probably attributable to uncertainties in the beta-to- $\nu_e$  conversion.”
  - “Yes: the deficit could result from short-baseline sterile neutrino oscillations.”

We need more data!!



P. Vogel, Caltech



The rest of us



T. Lasserre,  
CEA, France



P. Huber,  
VTech

# Reactor Anomaly Explanations

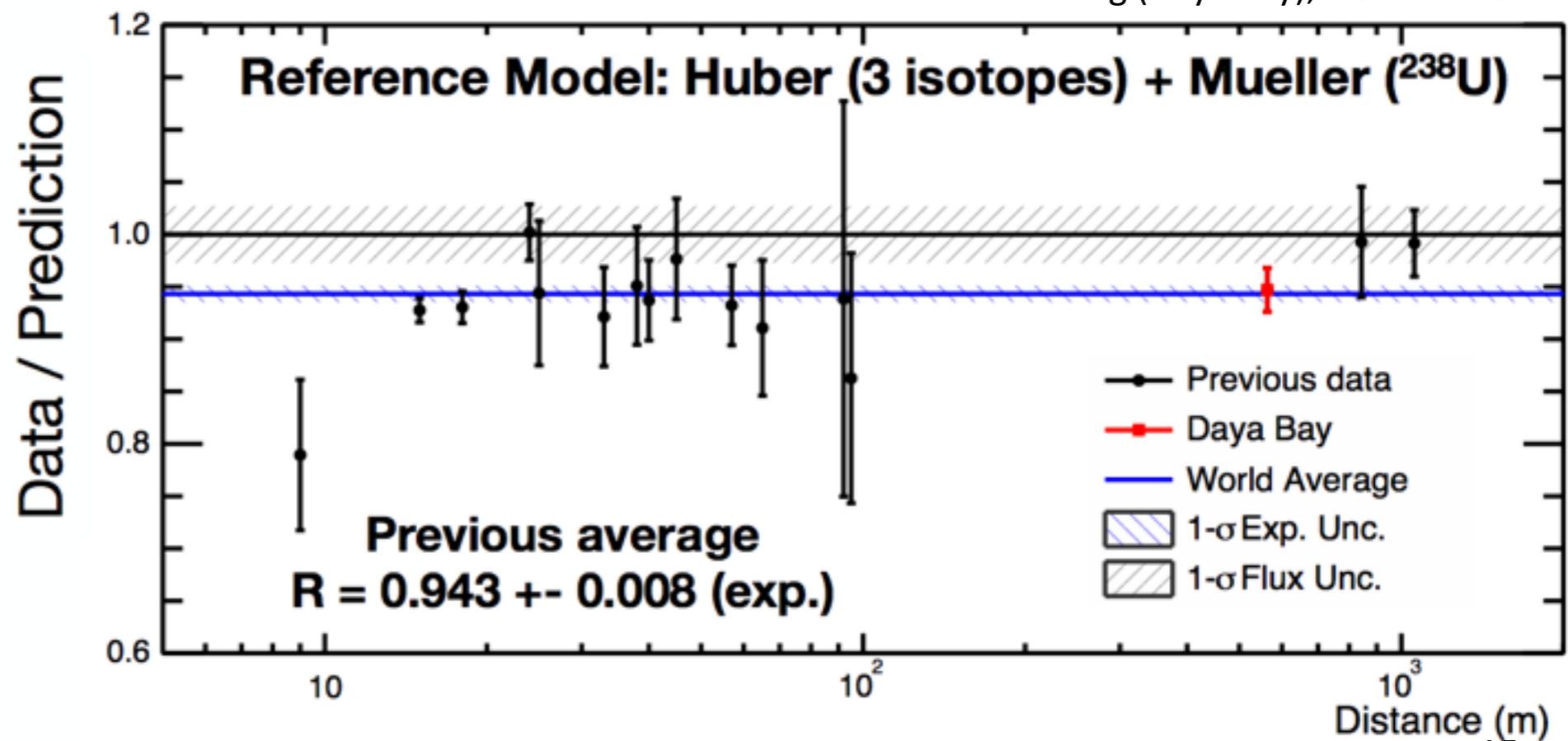


- Do we have a ‘reactor antineutrino anomaly?’
  - “No: the previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time”
- Daya Bay also sees the reactor flux deficit
  - 5% deficit relative to 2011 Huber/Mueller flux prediction
  - Blind analysis: No reactor power data available until analysis is totally fixed

C. Zhang (Daya Bay), Neutrino2014

C. Zhang (Daya Bay)  
Neutrino 2014

We need more data!!

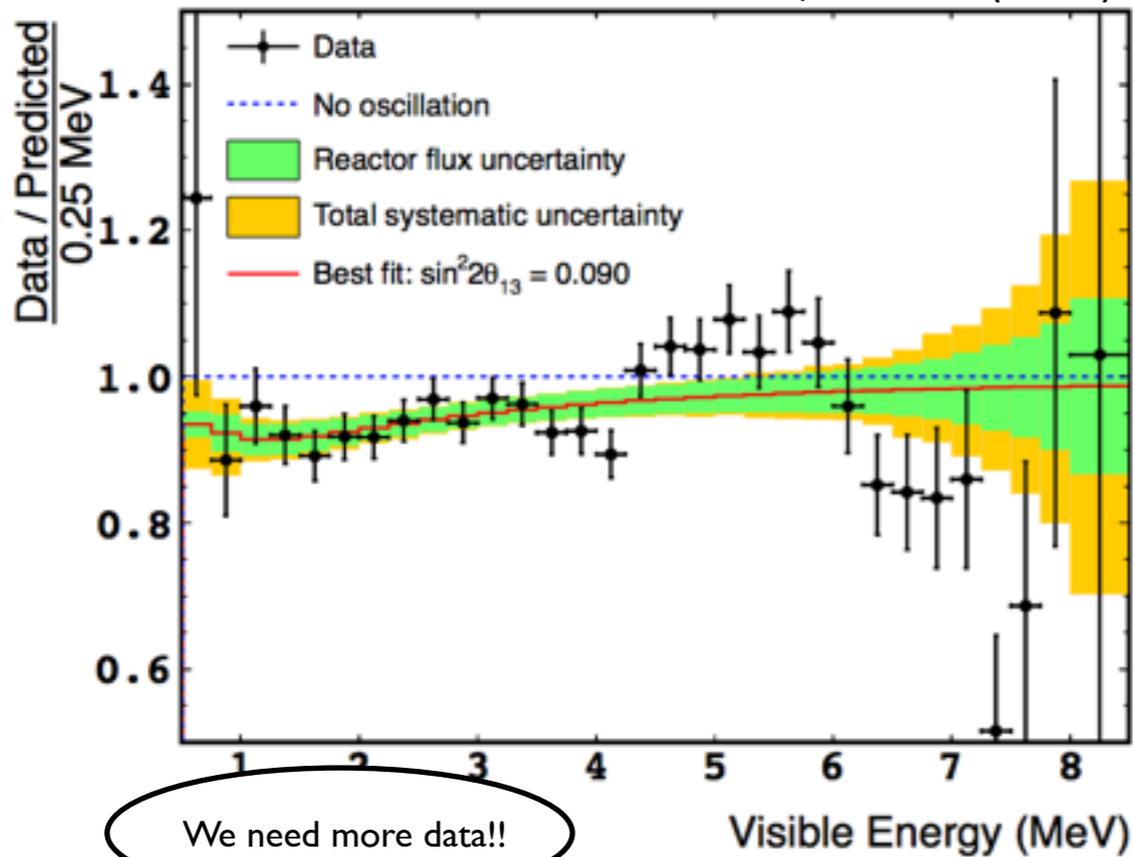




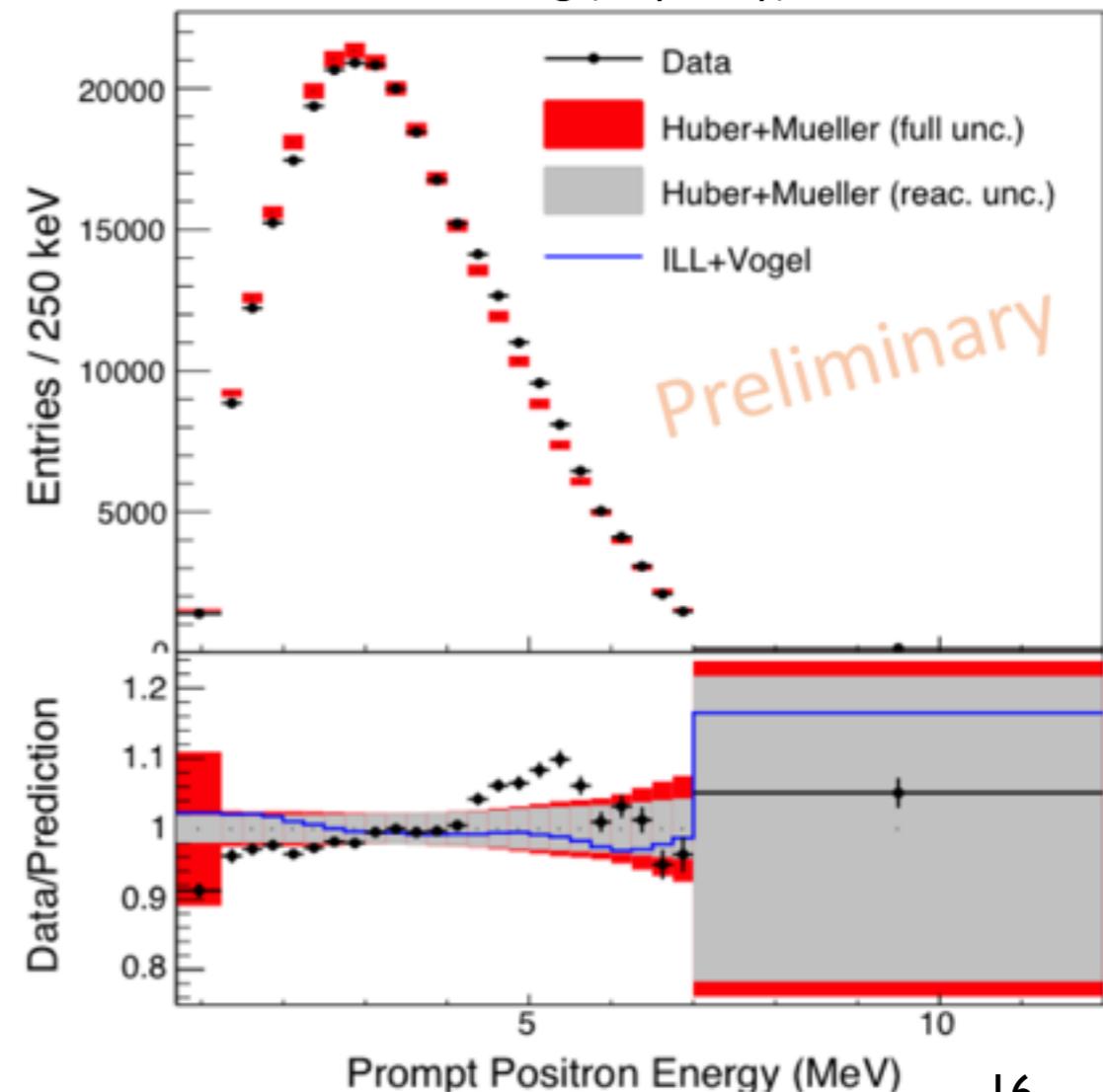
# Reactor Anomaly Explanations

- Do we have a ‘reactor antineutrino anomaly?’
  - “Yes: it’s probably attributable to problems in the beta-to- $\nu_e$  conversion”
- Spectra from  $\theta_{13}$  experiments disagree with predictions
  - “If measured spectrum doesn’t match, why should measured flux?”

Double Chooz, JHEP 10 (2014)



W. Zhong (Daya Bay) ICHEP 2014



# Reactor Antineutrino Explanations

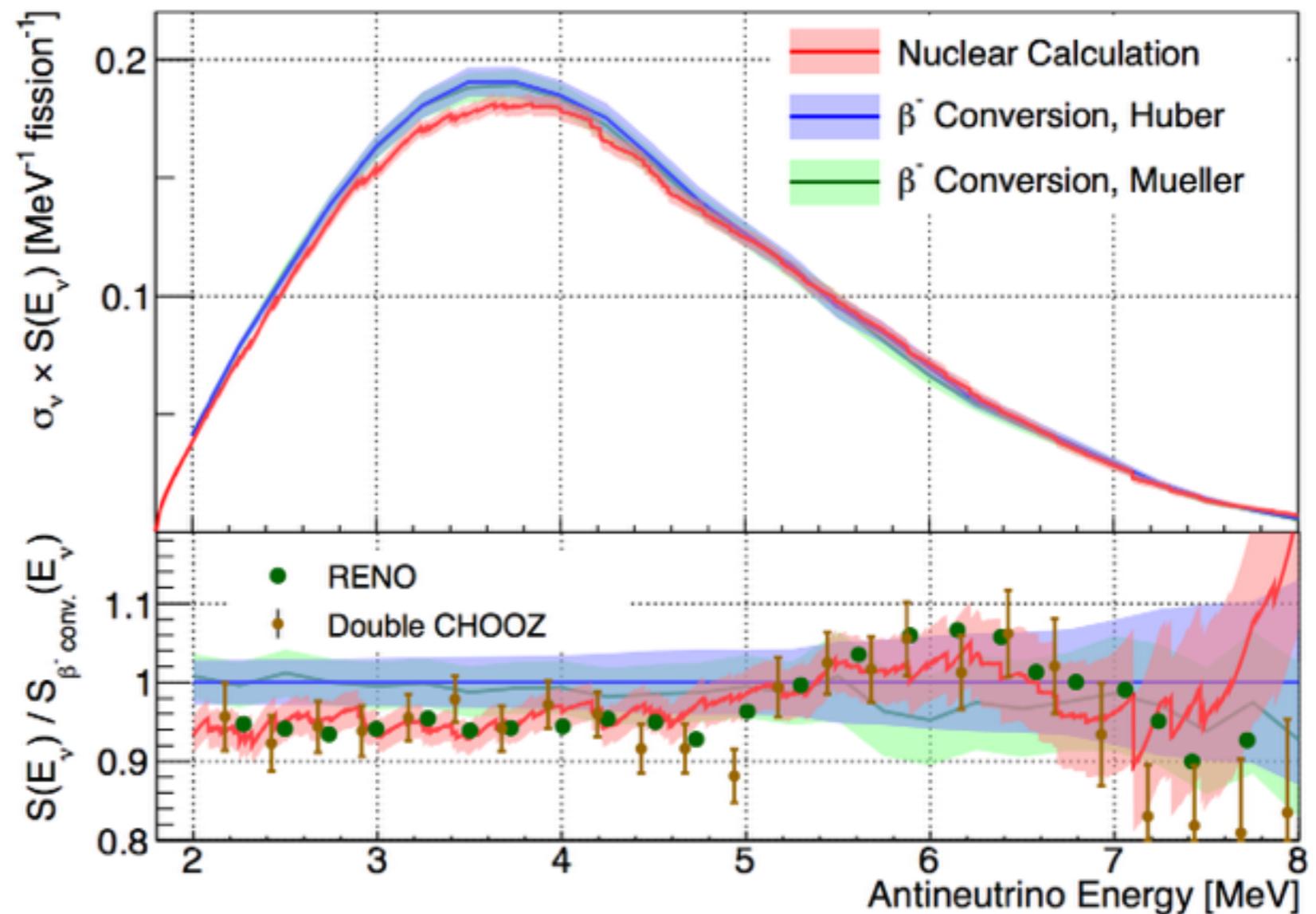


- Do we have a ‘reactor antineutrino anomaly?’
  - “Yes: it’s probably attributable to problems in the beta-to- $\nu_e$  conversion”
- New *ab initio* shape seems to match RENO/DC data quite well



- But not the flux...?
- Not enough data to constrain this situation further!

Dwyer and Langford, PRL 114 (2015)



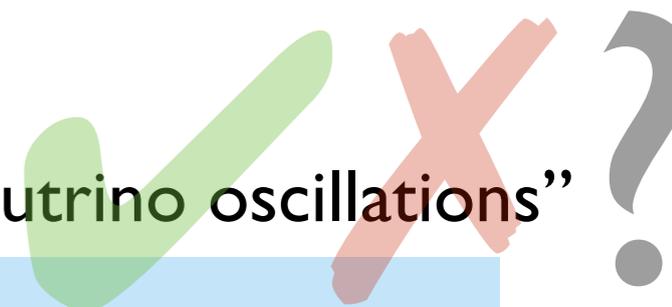
We need more data!!



# Reactor Anomaly Explanations



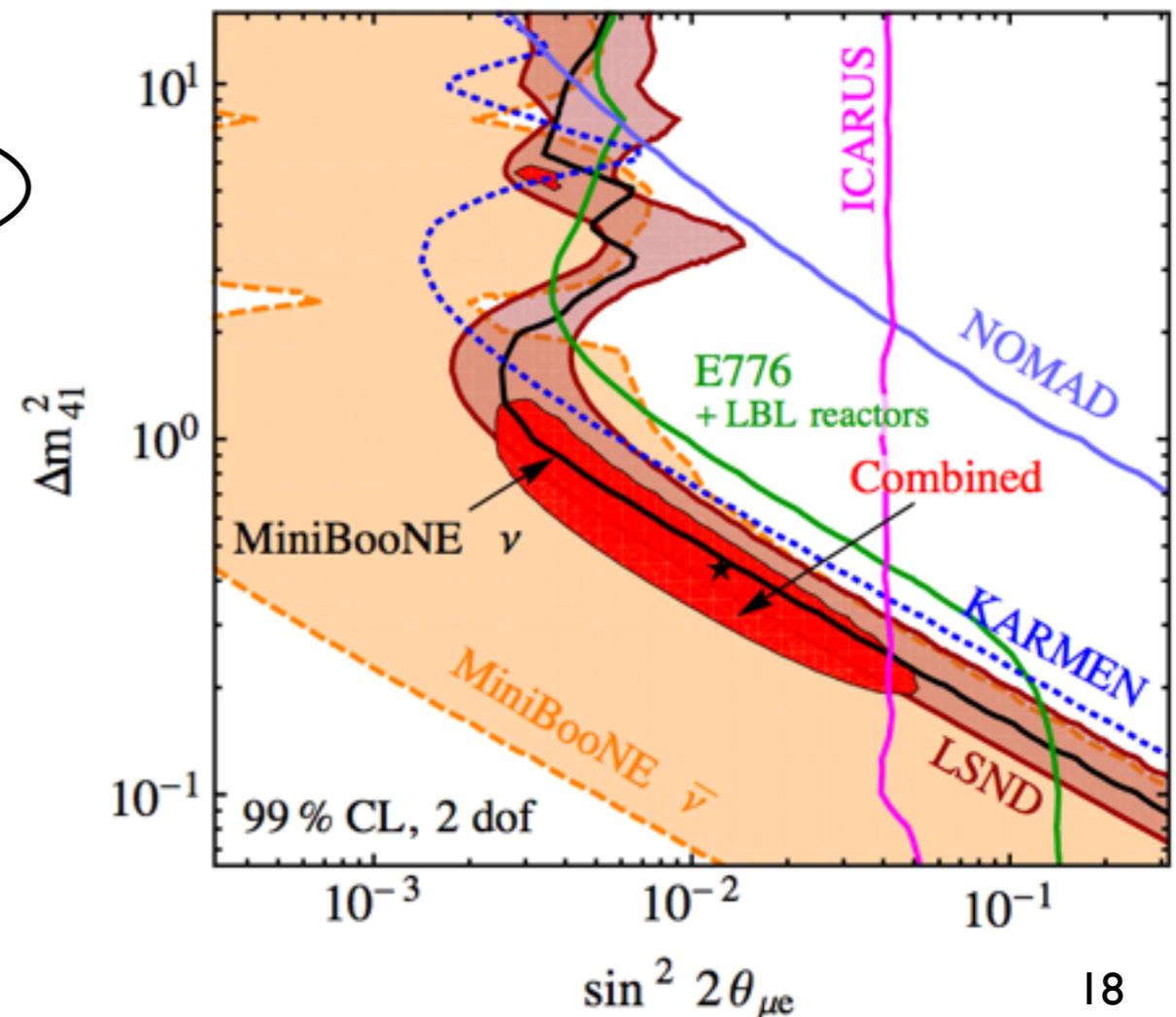
- Do we have a ‘reactor antineutrino anomaly?’
  - “Yes: the deficit could result from short-baseline sterile neutrino oscillations”
- Consistent with existing hints for 1 eV sterile neutrinos
  - However, tension with null  $\nu_\mu$  disappearance measurements...
- Also, to be able to tell if CP-violation exists, we need to know if sterile neutrinos exist...



We need more data!!



Boris Kayser, Fermilab



# Outline



- Intro: Reactor  $\bar{\nu}_e$  Flux and Spectrum Predictions
- Reactor Anomaly and recent flux/spectrum measurements
- Measurement of the  $\bar{\nu}_e$  spectrum at PROSPECT
- Current context for PROSPECT

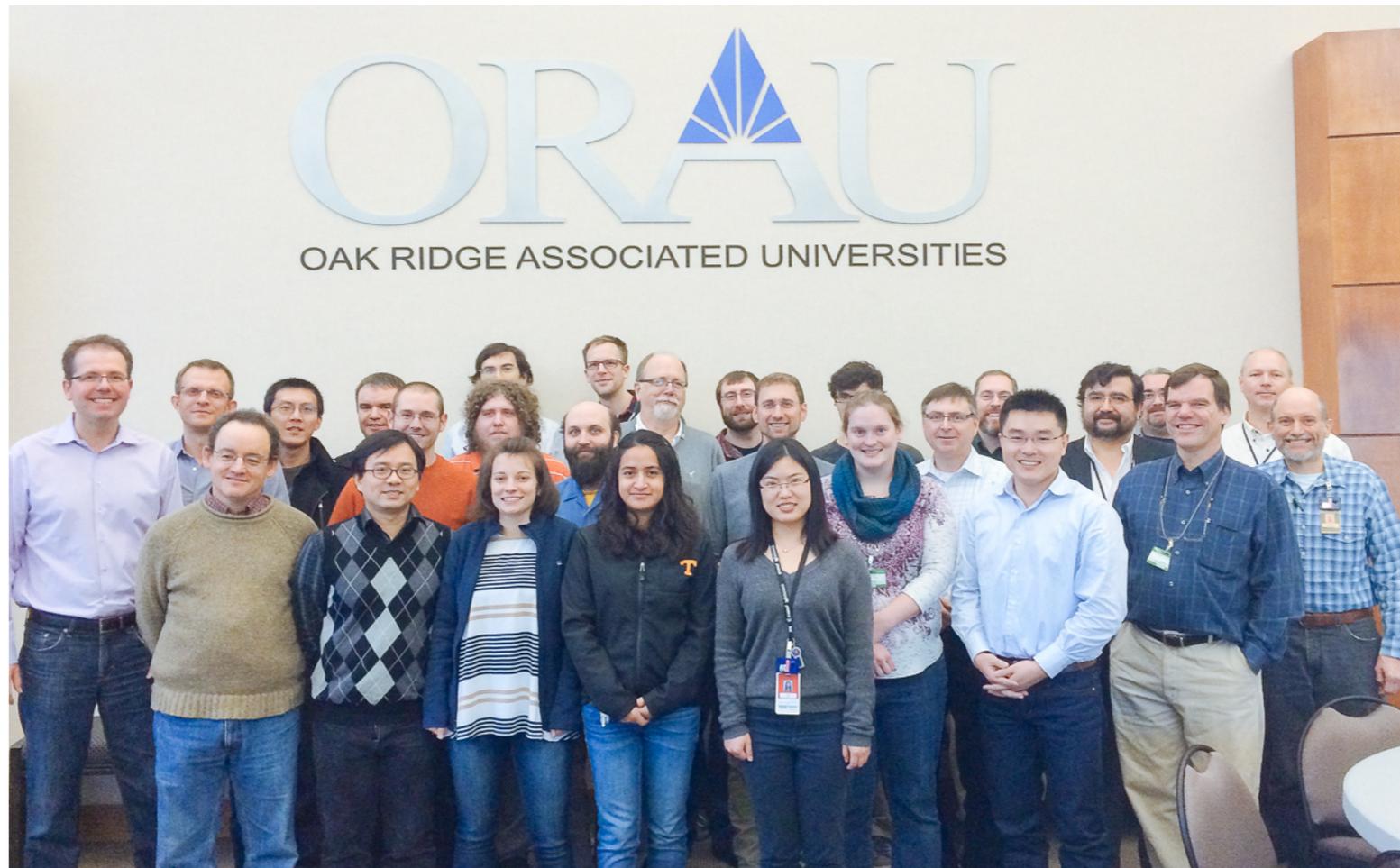
PROSPECT20 meter-long cell



# Precise Reactor Spectrum Measurements



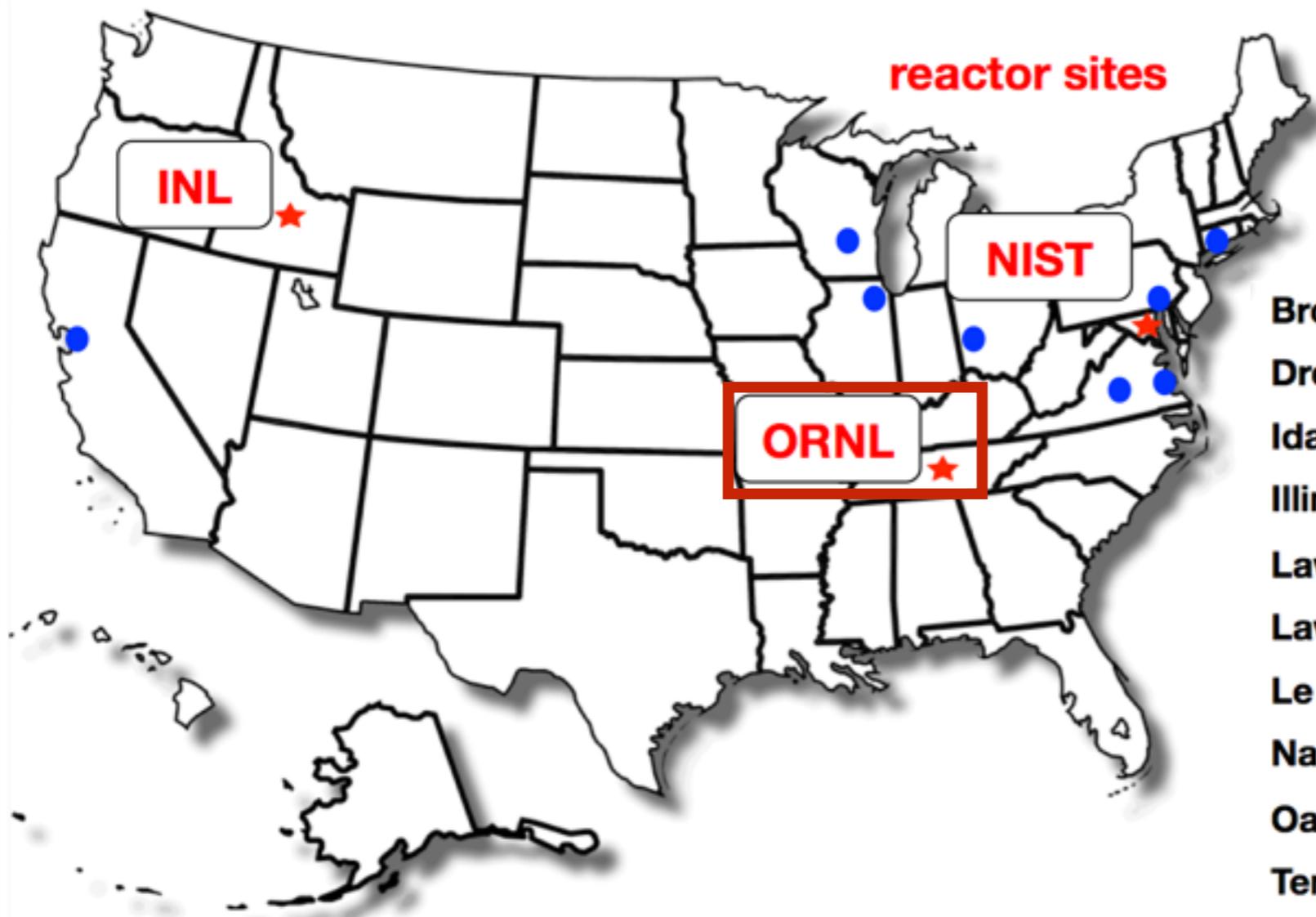
- A lot yet to be learned from/about reactor  $\bar{\nu}_e$  spectra
- In particular we could really use:
  - A high energy-resolution detector for precisely measuring absolute spectrum
  - A high position-resolution detector for comparing spectra between baselines
- Enter **PROSPECT**: the **P**recision **R**eactor **O**scillation and **SPECT**rum Experiment



# PROSPECT Collaboration



## PROSPECT Collaboration



- Brookhaven National Laboratory
- Drexel University
- Idaho National Laboratory
- Illinois Institute of Technology
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Le Moyne College
- National Institute of Standards and Technology
- Oak Ridge National Laboratory
- Temple University
- University of Tennessee
- Virginia Tech University
- University of Waterloo
- University of Wisconsin
- College of William and Mary
- Yale University

**10 universities**  
**6 national laboratories**

Updated whitepaper  
arXiv:1309.7647

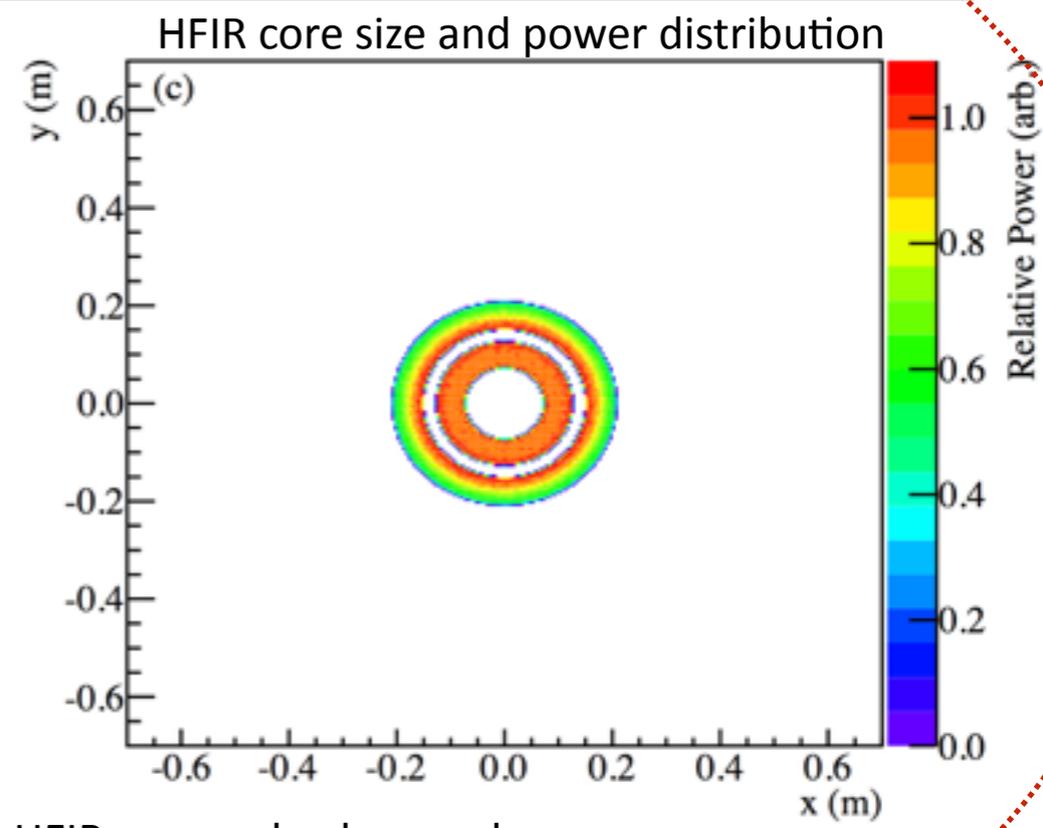
Website  
<http://prospect.yale.edu/>

# High-Flux Isotope Reactor at ORNL



- Compact 85MW Core
- HEU: constant U-235  $\bar{\nu}_e$  spectrum
- 42% reactor up-time (5 yearly cycles)
- Available detector location at 6+ m
- Have surveyed reactor backgrounds

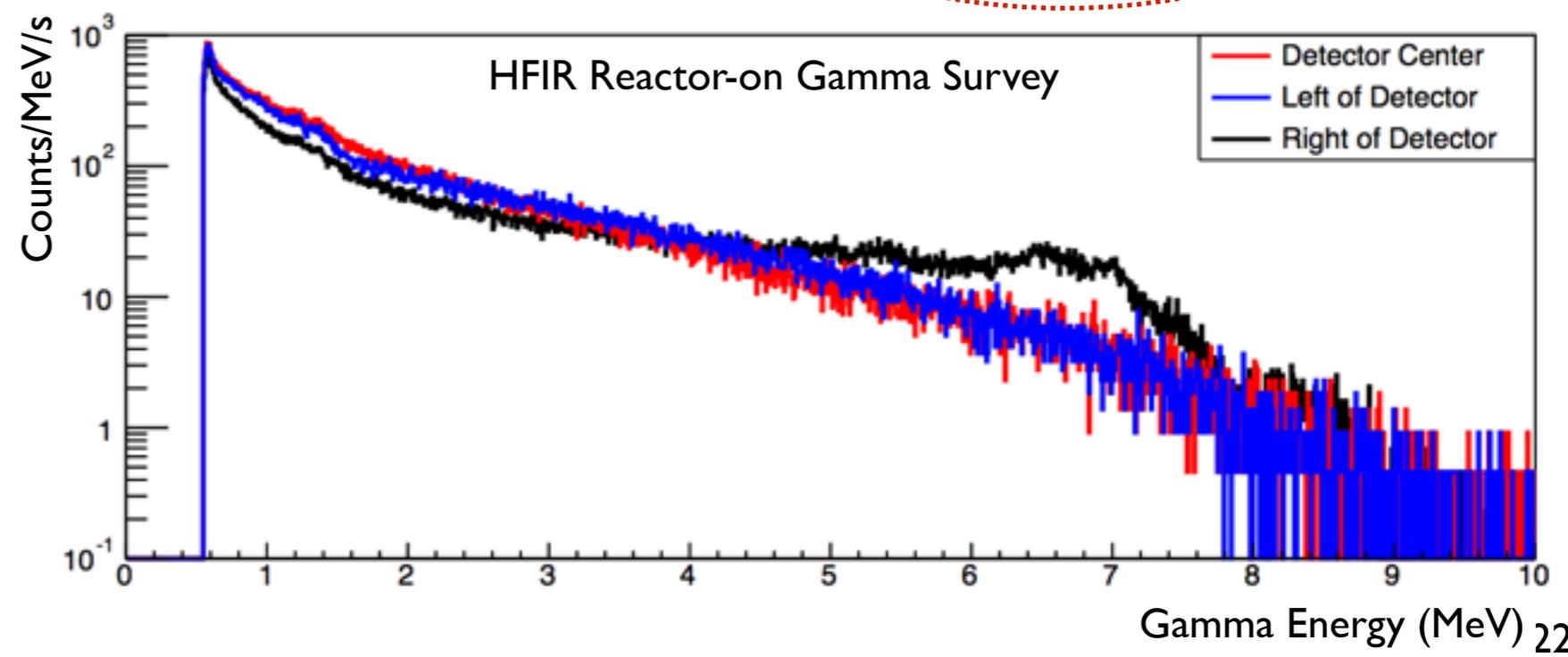
Commercial core size



HFIR core viewed from above



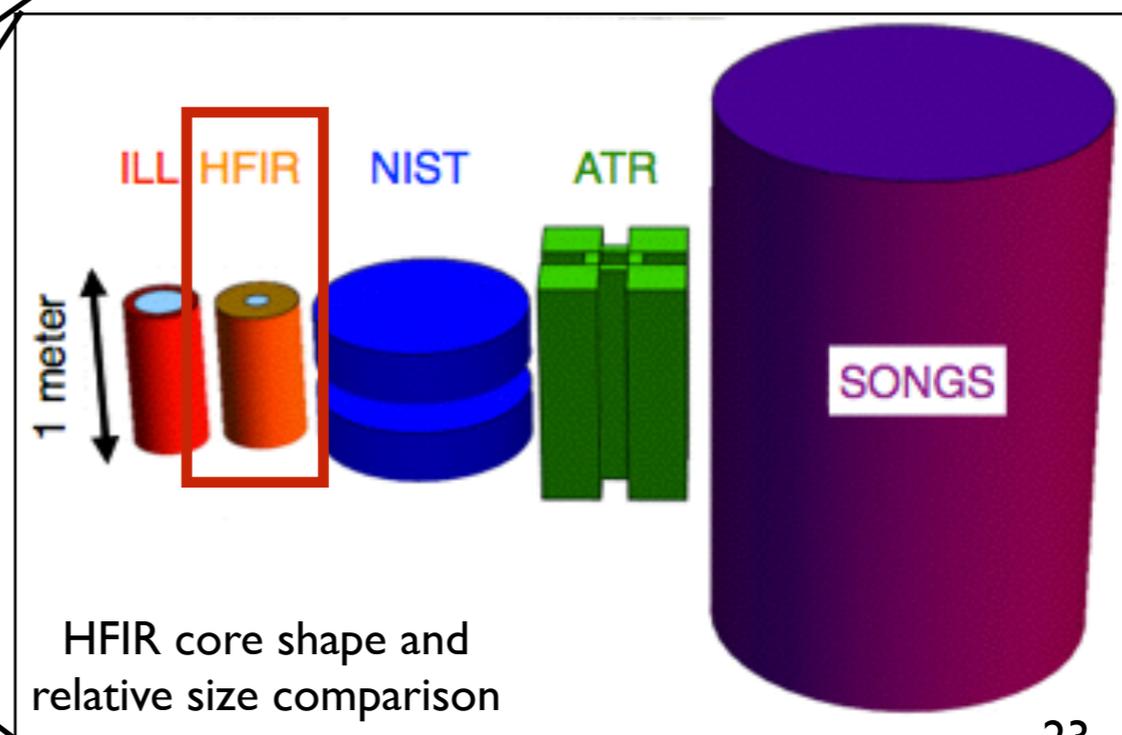
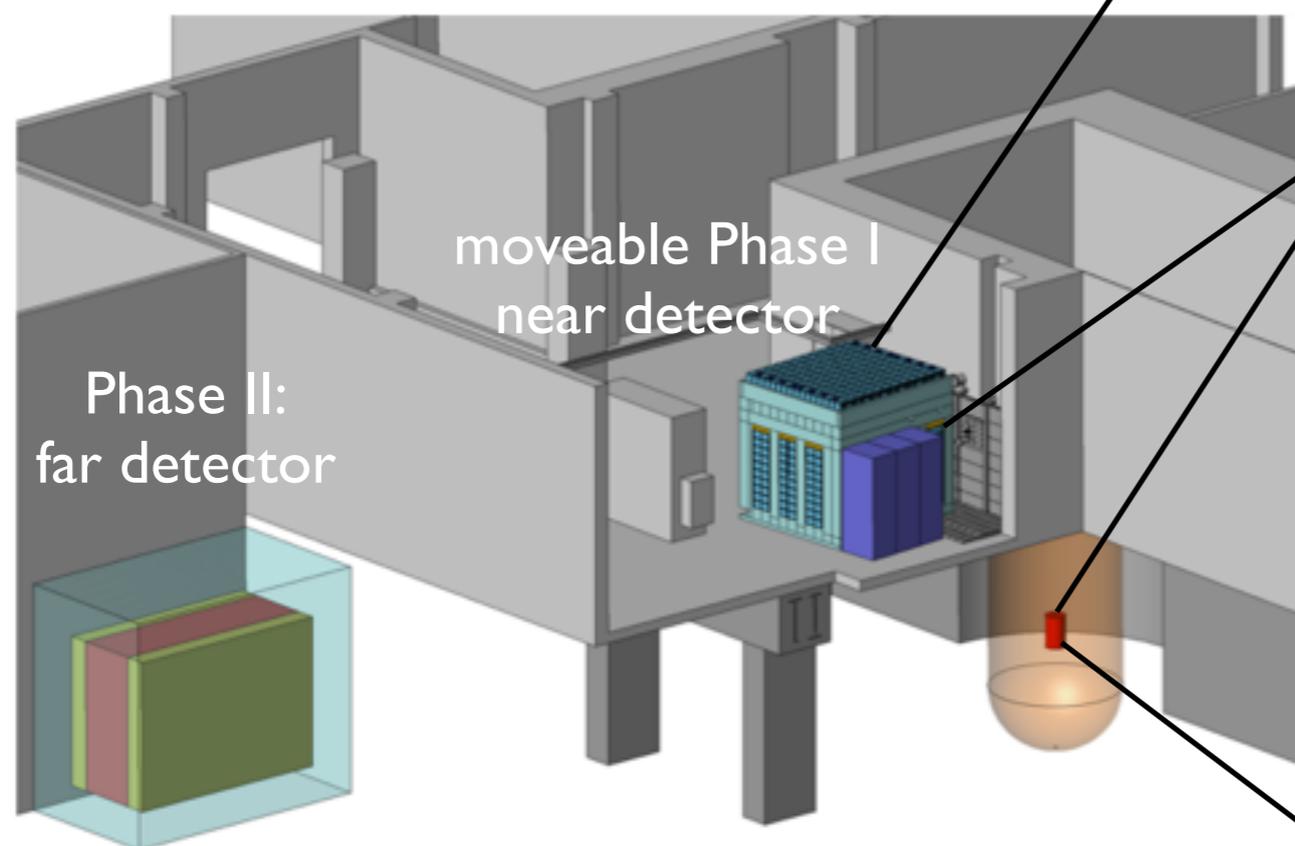
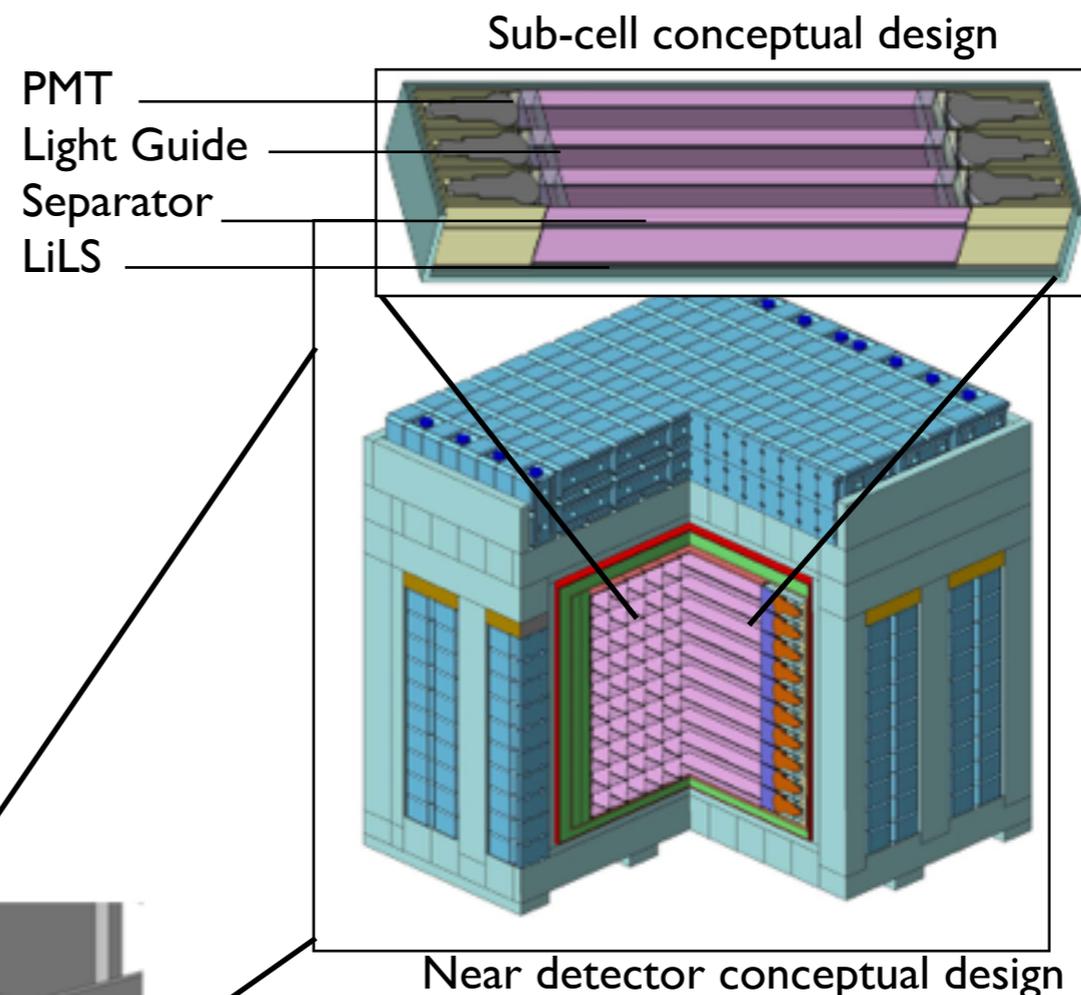
HFIR gamma background survey



# PROSPECT Experimental Layout

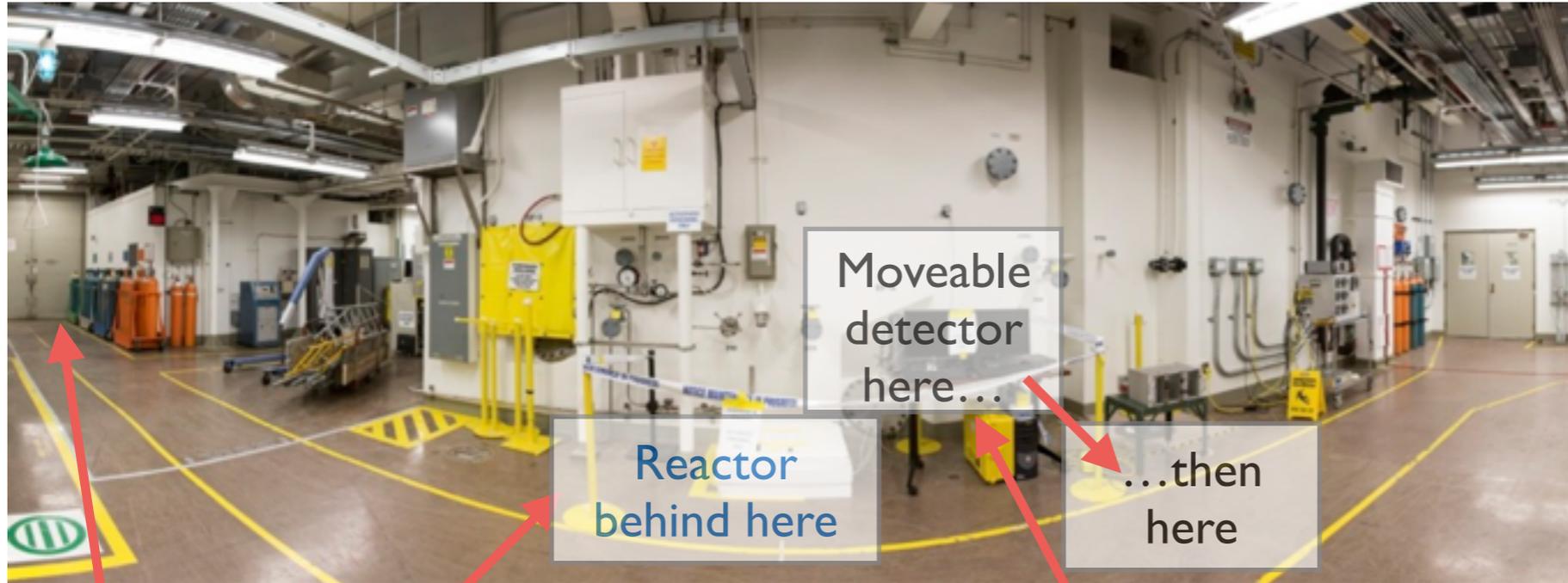


- High Flux Isotope Reactor: ORNL
- Extensive passive shielding
- Segmented liquid scintillator target region: ~3 tons for near detector (Phase I)
- Moveable: 7-12 m baselines



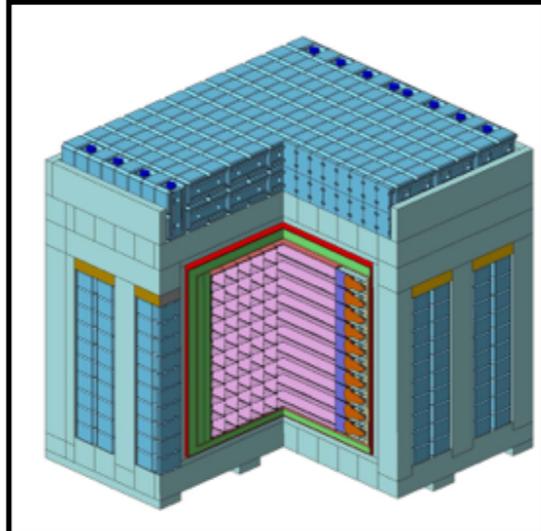
Two-detector PROSPECT deployment at HFIR

# PROSPECT Location at HFIR

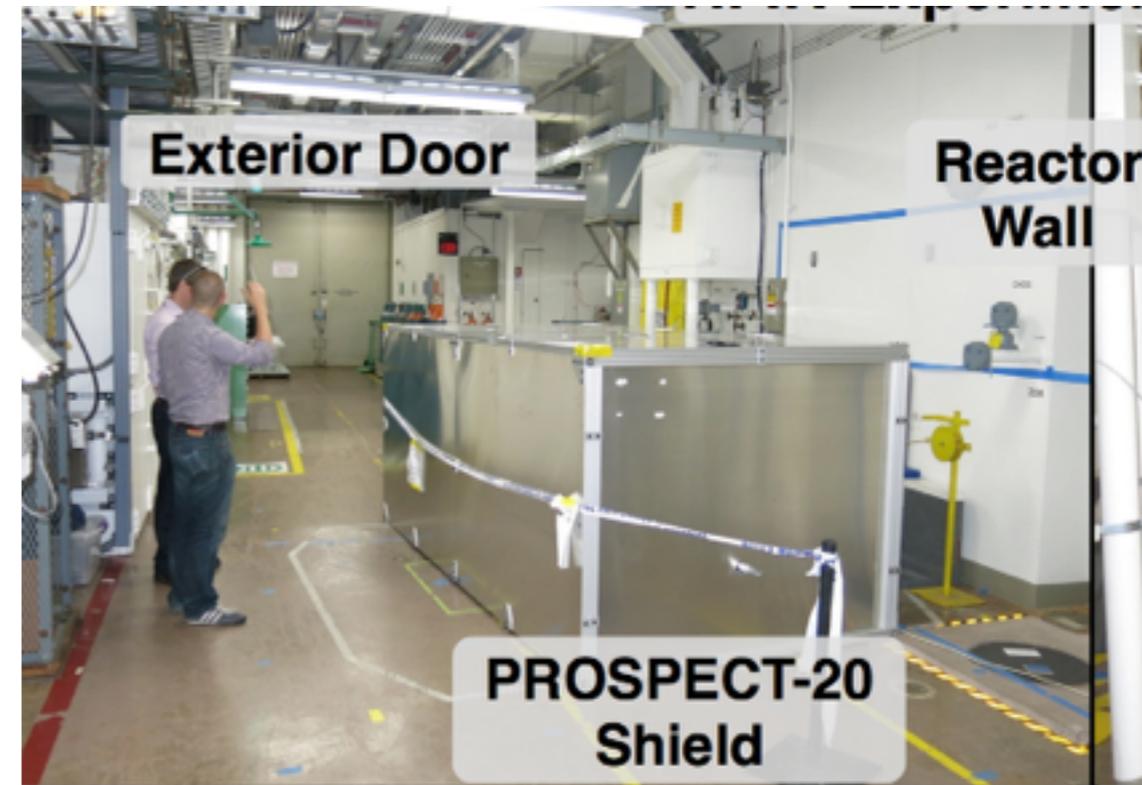


## HFIR Main Level Hallway

Wide door to grade level: bring detector subsystems in here



### PROSPECT Prototype and shielding at HFIR

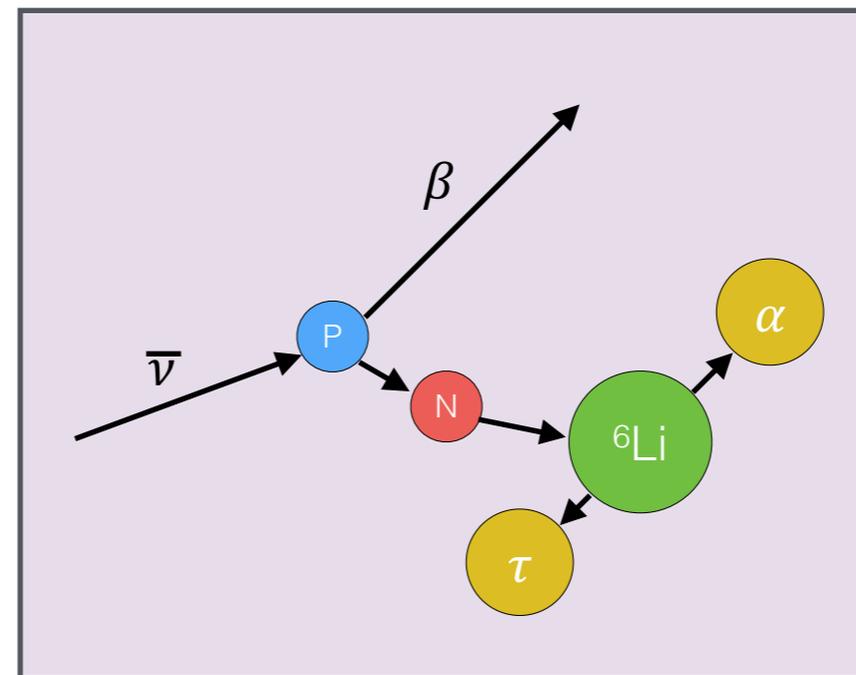
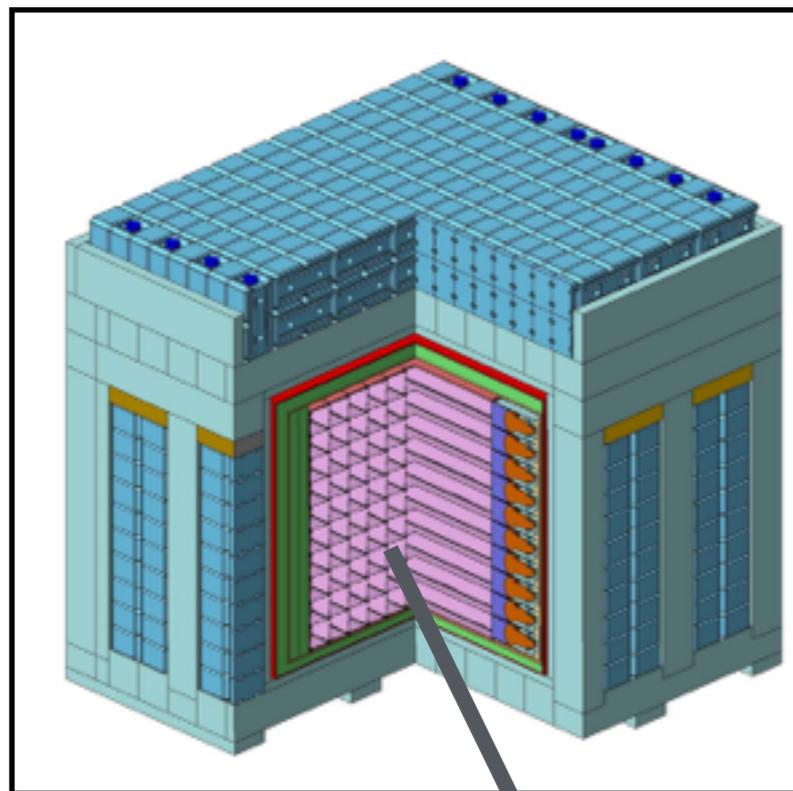


Have been working in this location for > 1 year; PROSPECT prototypes operating here since August 2014!

# IBD Detection in Target



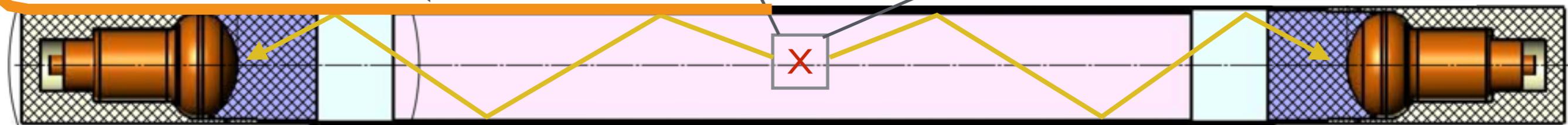
- Inverse beta interactions in Li-loaded PSD liquid scintillator
- 10 x 14 optically decoupled cells:  $\sim 15\text{cm} \times 15\text{cm} \times 100\text{cm}$  each
- Specularly reflecting cell walls quickly guide light to PMTs
- System can meet position/energy resolution requirements



Prompt signal: 1-10 MeV  
positron from inverse  
beta decay (IBD)

Delay signal:  $\sim 0.5$  MeV  
signal from neutron  
capture on  ${}^6\text{Li}$

Calibration sources



# PROSPECT Prototype Demonstrations



Run DAQ,  
Remote data-taking

See n-Li + PSD

PROSPECT 0.1\*  
Aug 2014



2 inches



Demonstrate shielded  
background rates

Demonstrate full  
timing and PE response

PROSPECT 2\*  
Dec 2014 -  
Mar 2015



5 inches

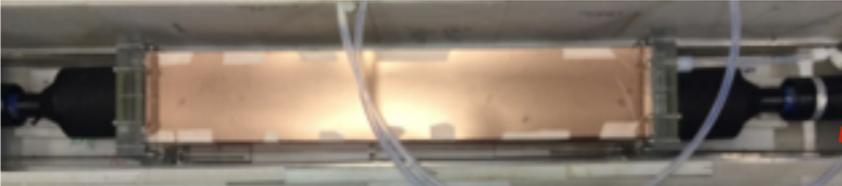


Deploy final design concepts  
Observe relative segment responses

See antineutrinos

Meet physics goals

PROSPECT 20\*  
Mar 2015

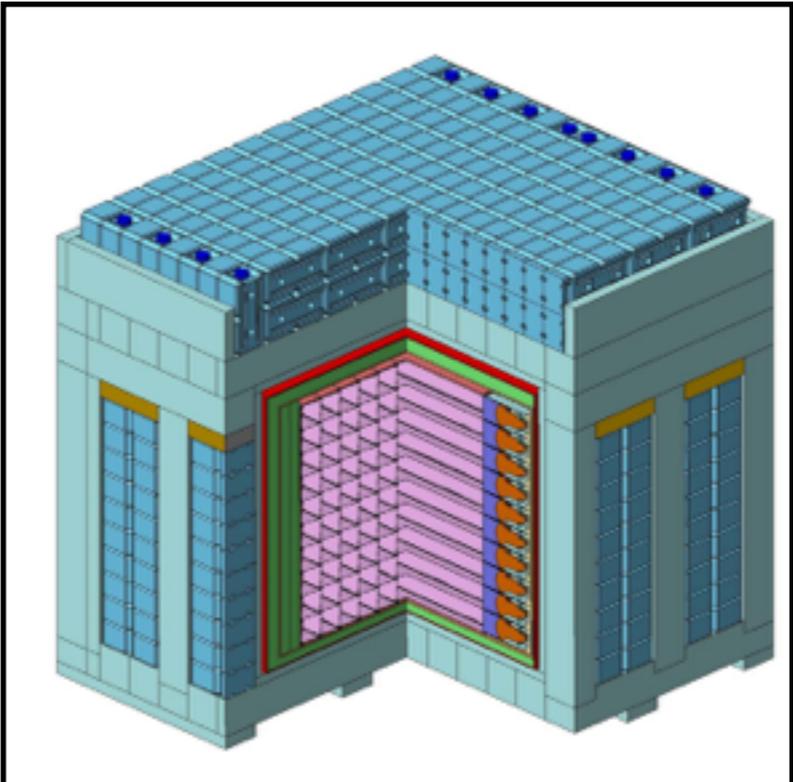


1 meter

Deploy final design concepts  
Observe relative segment responses

PROSPECT 60  
Jan 2016

PROSPECT 2ton



\* Deployment complete!!!!

Approximate mass kg

# PROSPECT Prototype Demonstrations



- ✓ Run DAQ, Remote data-taking
- ✓ See n-Li + PSD

**PROSPECT 0.1\***  
Aug 2014



2 inches

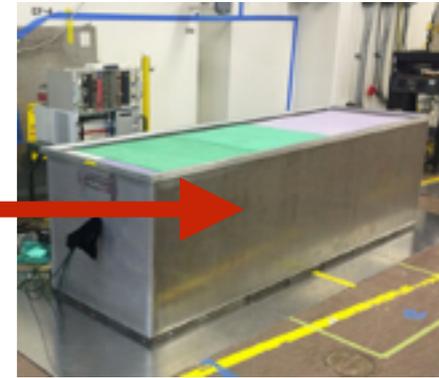
arXiv:1506.03547 (2015)

- ✓ Demonstrate shielded background rates
- ✓ Demonstrate full timing and PE response

**PROSPECT 2\***  
Dec 2014 - Mar 2015



5 inches



arXiv:1508.56575 (2015)

**PROSPECT 20\***  
Mar 2015



1 meter

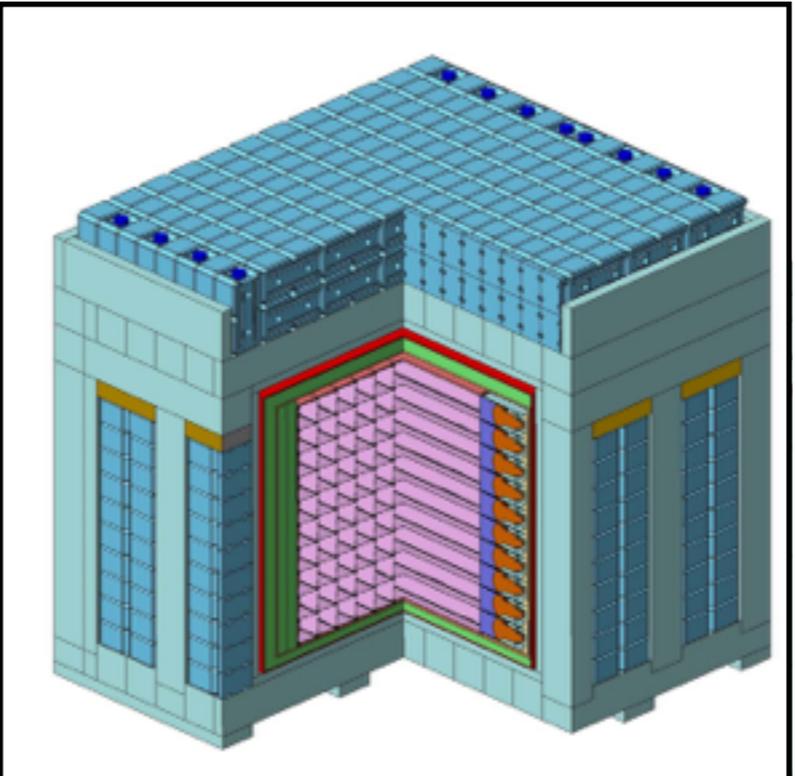


- Deploy final design concepts
- Observe relative segment responses

**PROSPECT 60**  
Jan 2016

- See antineutrinos
- Meet physics goals

**PROSPECT 2ton**



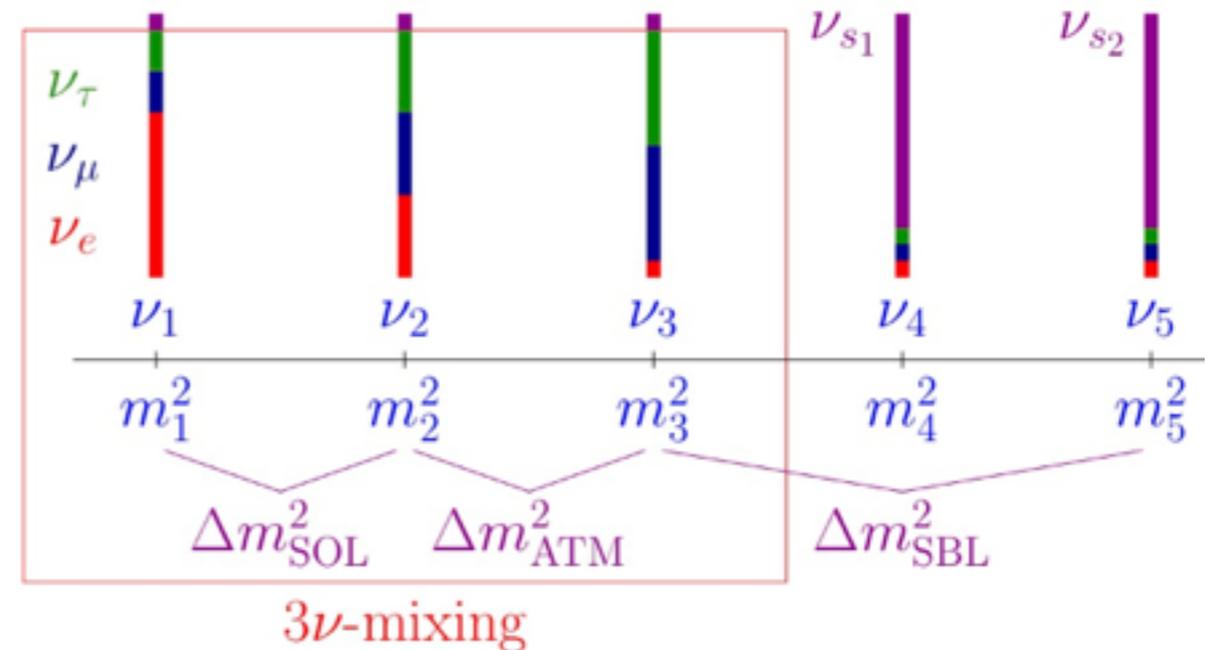
\* Deployment complete!!!!

Approximate mass kg

# PROSPECT Physics: Oscillations

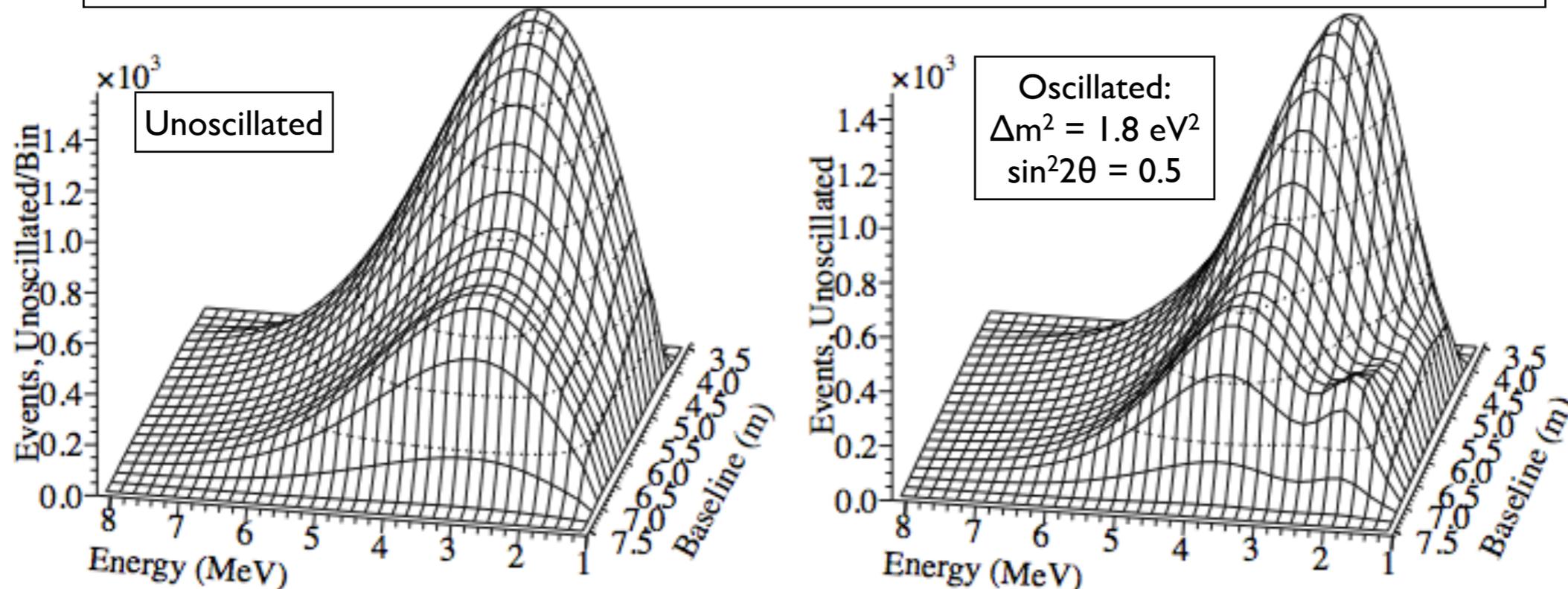


- Measure energy spectrum separately in each segment
- Look for unexpected L/E distortion: oscillations
- Mass splitting wouldn't match observed three-neutrino splittings: fourth (sterile) neutrino



$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \left[ 1.27 \Delta m^2 (eV^2) \frac{L(km)}{E_\nu(GeV)} \right]$$

Example: 3x1x1 m<sup>3</sup> detector, 1m<sup>3</sup> 20 MW HEU core, 4m closest distance



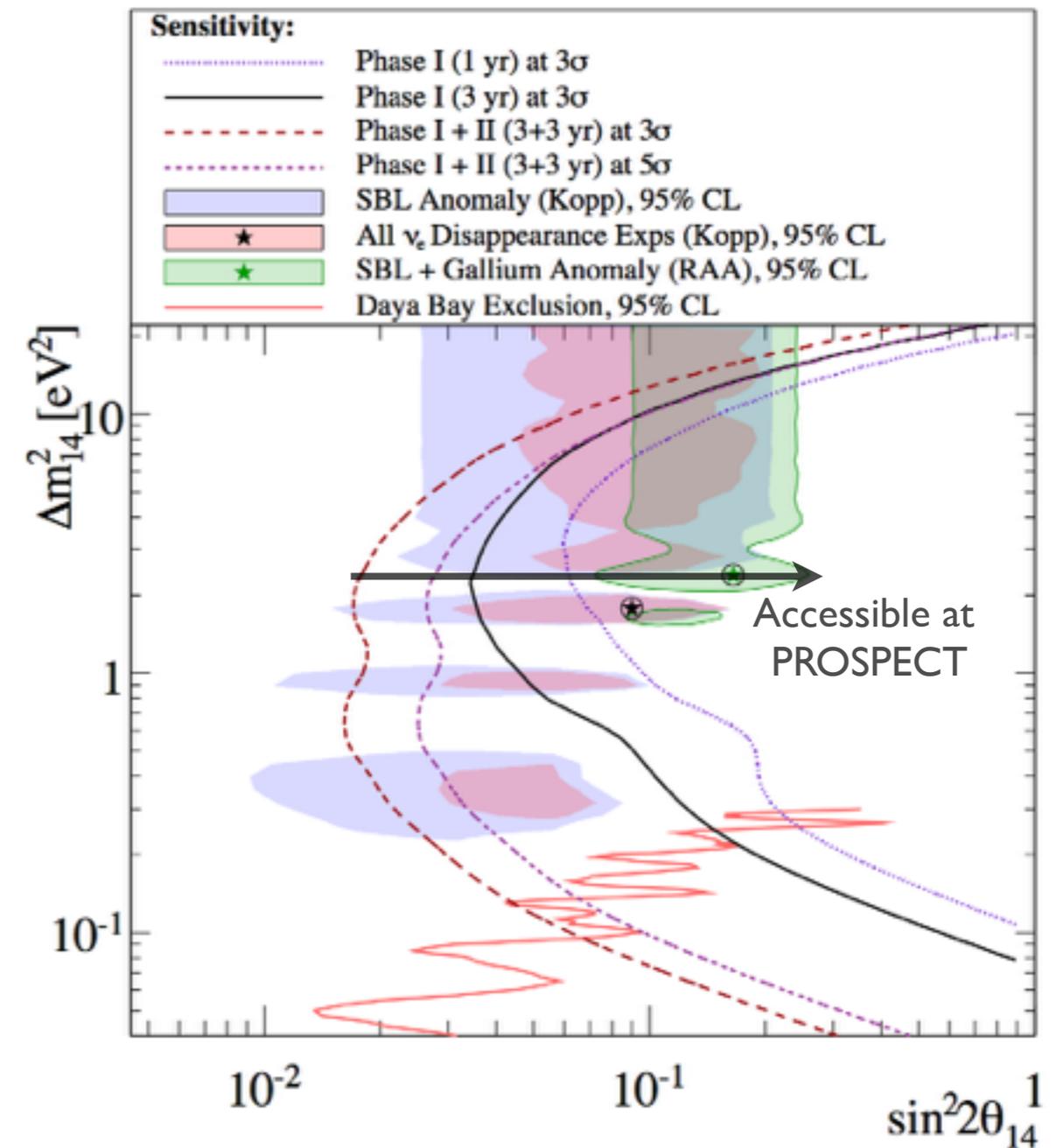
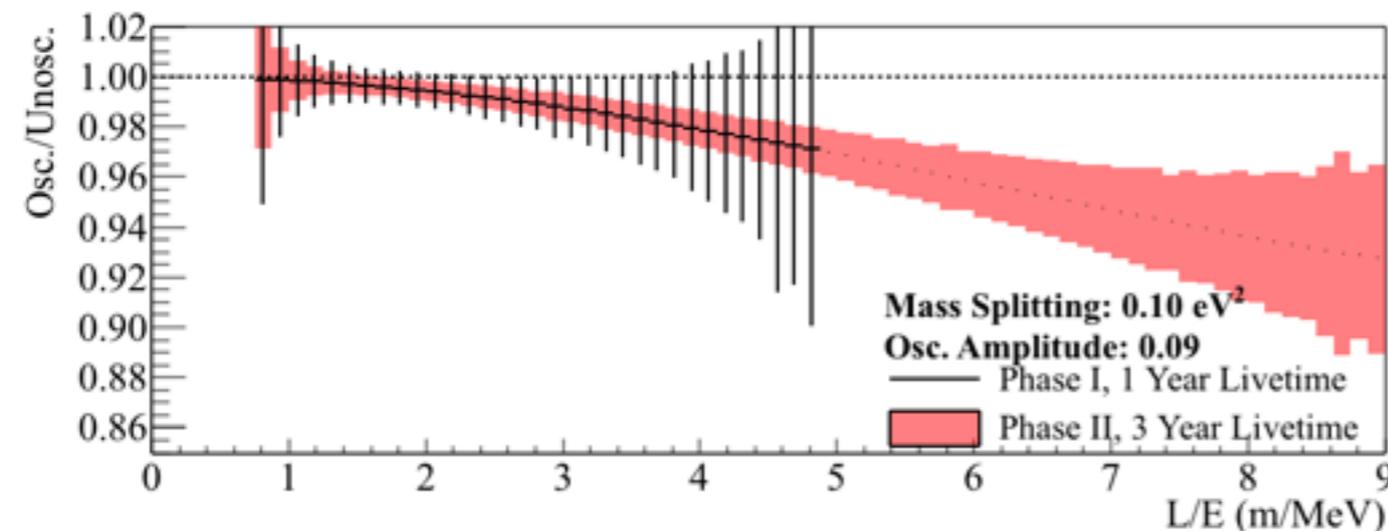
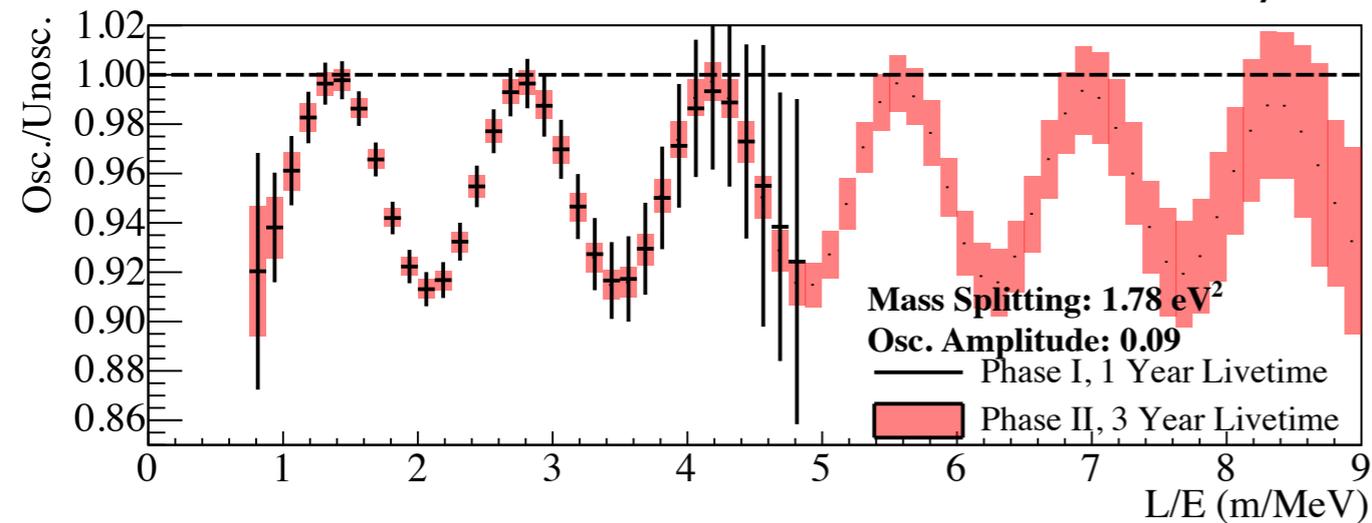
# PROSPECT Physics: Oscillations



## ● Excellent oscillation discovery potential at PROSPECT

- If new sterile neutrino is where global fits suggest, it's very likely we'll see it!
- No reliance on absolute spectral shape or normalization: pure relative measurement
- Good coverage with a single detector and one/three calendar years of data-taking

Simulated PROSPECT data, binned in L/E; Stat err. only



# PROSPECT Physics: Absolute Spectrum



## ● What is the correct model?

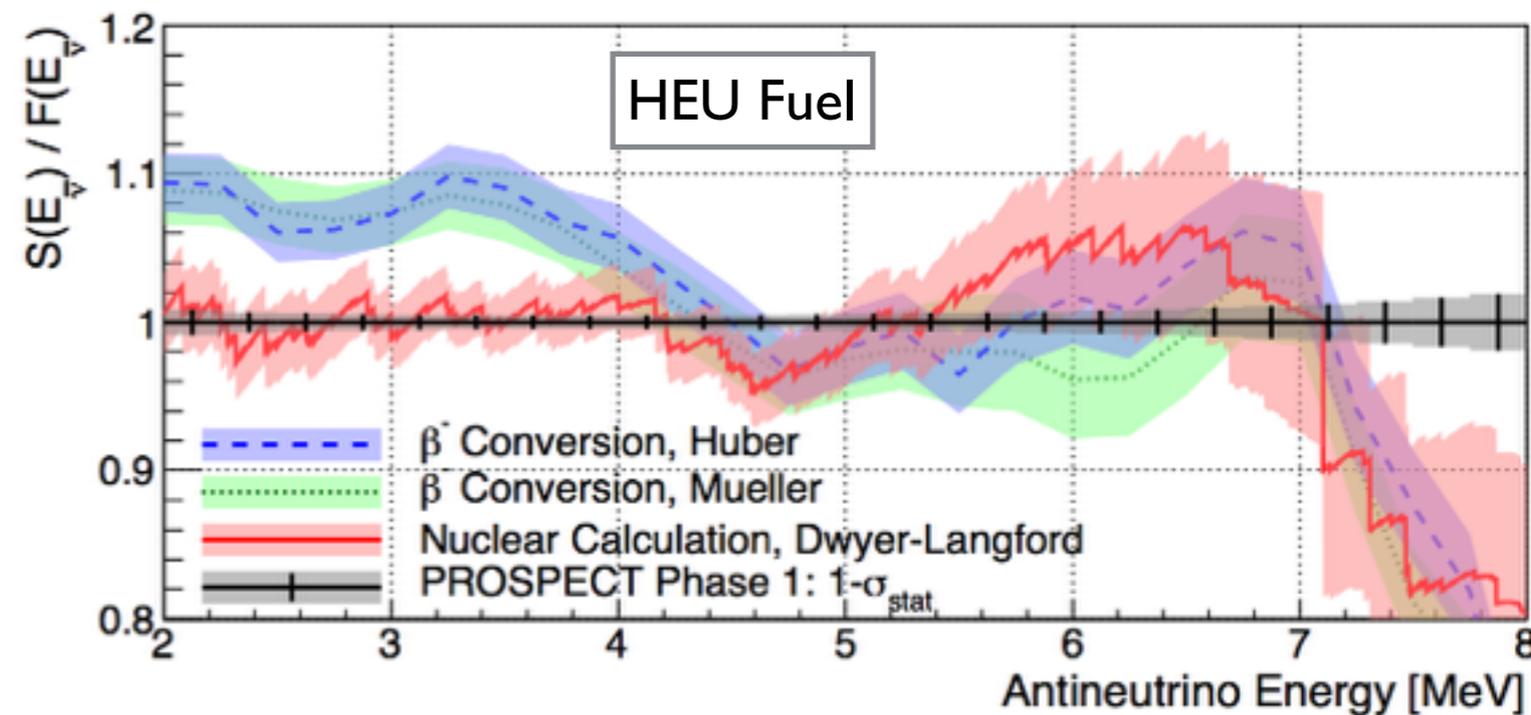
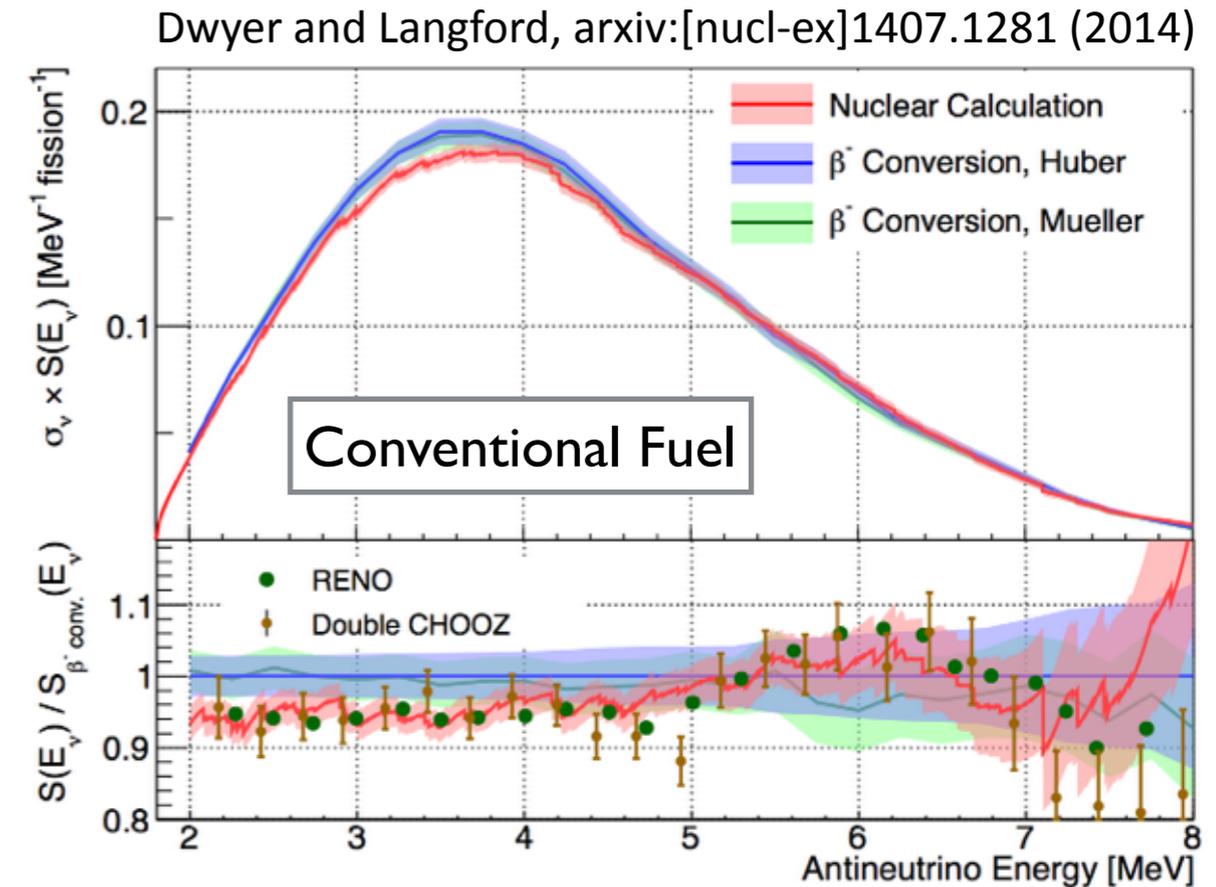
- Have data points for conventional fuel ( $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$ )
- HEU ( $^{235}\text{U}$ ): independent constraint

## ● Benefits of HFIR:

- 1 core versus many cores (Daya Bay, RENO)
- Easier model: only 1 isotope, no time-dependence

## ● Implications for reactor monitoring:

- Example: what if 5 MeV bump isn't present for HEU fuel?
- In that case, 'bump' size could be a proxy for  $^{239}\text{Pu}$  concentration in core



# Demonstrating Key Requirements

---



- To accomplish these physics goals, PROSPECT needs:
  - Control of backgrounds at on-surface near-reactor location
  - Understanding position reconstruction ability
  - Understanding of energy scale and energy resolution
- Pre-PROSPECT program should demonstrate PROSPECT's abilities in all three of these areas.

# IBD Detection and Backgrounds



- Have a highly sensitive detector operating at the surface in the direct vicinity of an operating nuclear reactor
- Major design challenge: background reduction
- Aiming for S:B ratio of 1:1
  - If we can achieve this, PROSPECT can meet the physics goals I discussed.

## Signal, Main Backgrounds

### Inverse Beta Decay

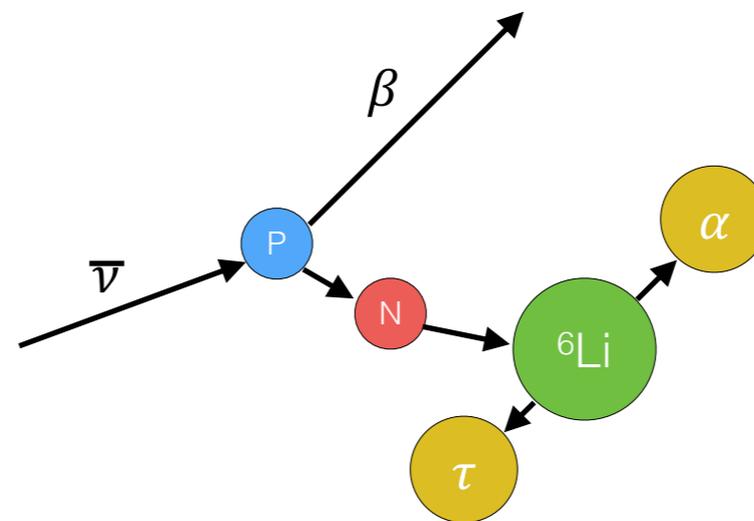
$\gamma$ -like prompt, n-like delay

### Fast Neutron

n-like prompt, n-like delay

### Accidentals

$\gamma$ -like prompt,  $\gamma$ -like delay



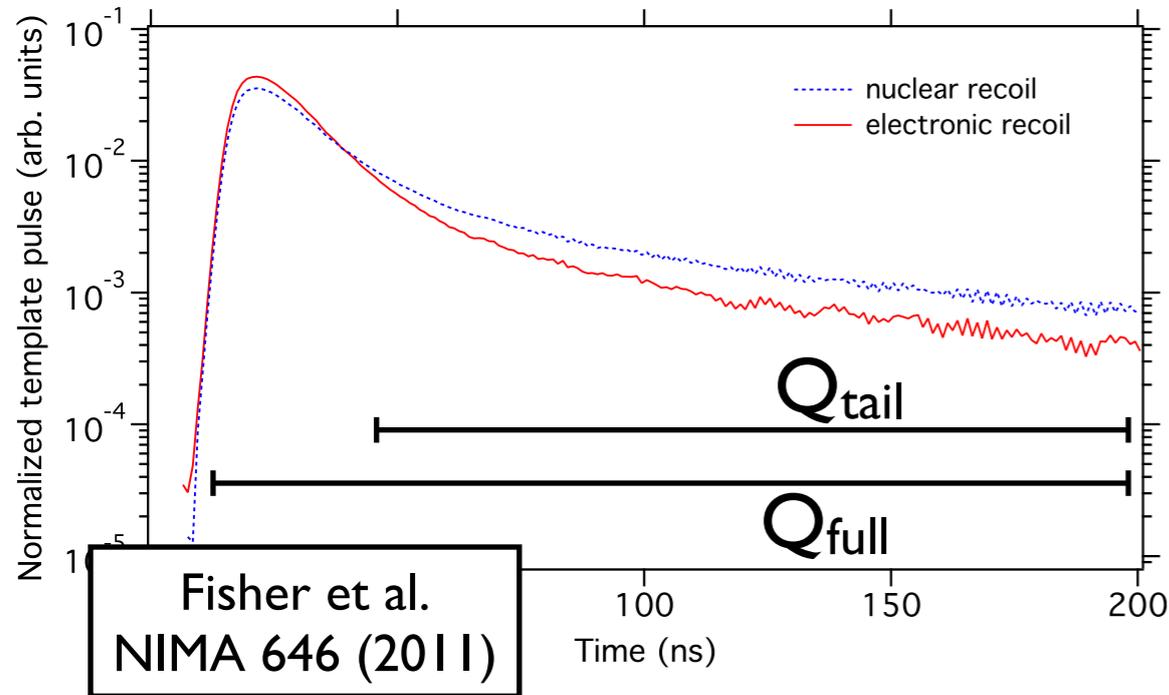
Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

Delay signal:  $\sim 0.5$  MeV signal from neutron capture on  ${}^6\text{Li}$

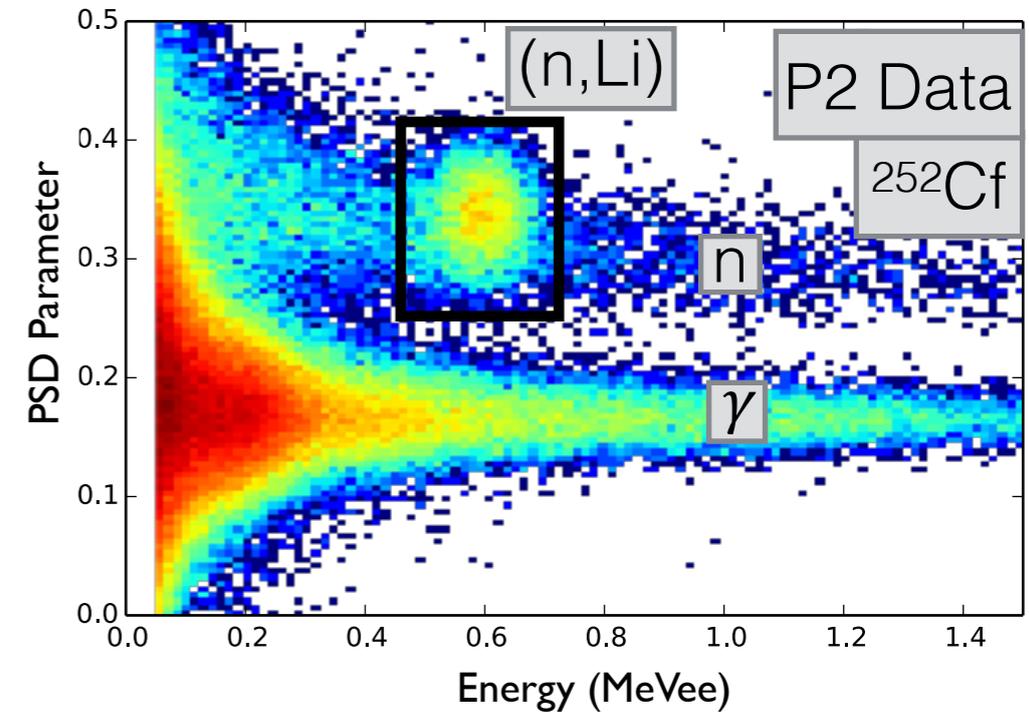
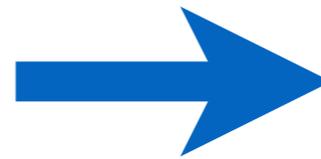
# Background Rejection, Signal Selection



- Reduce backgrounds: Li-capture and pulse-shape discrimination



$$PSD = \frac{Q_{tail}}{Q_{full}}$$



## Signal, Main Backgrounds

Inverse Beta Decay

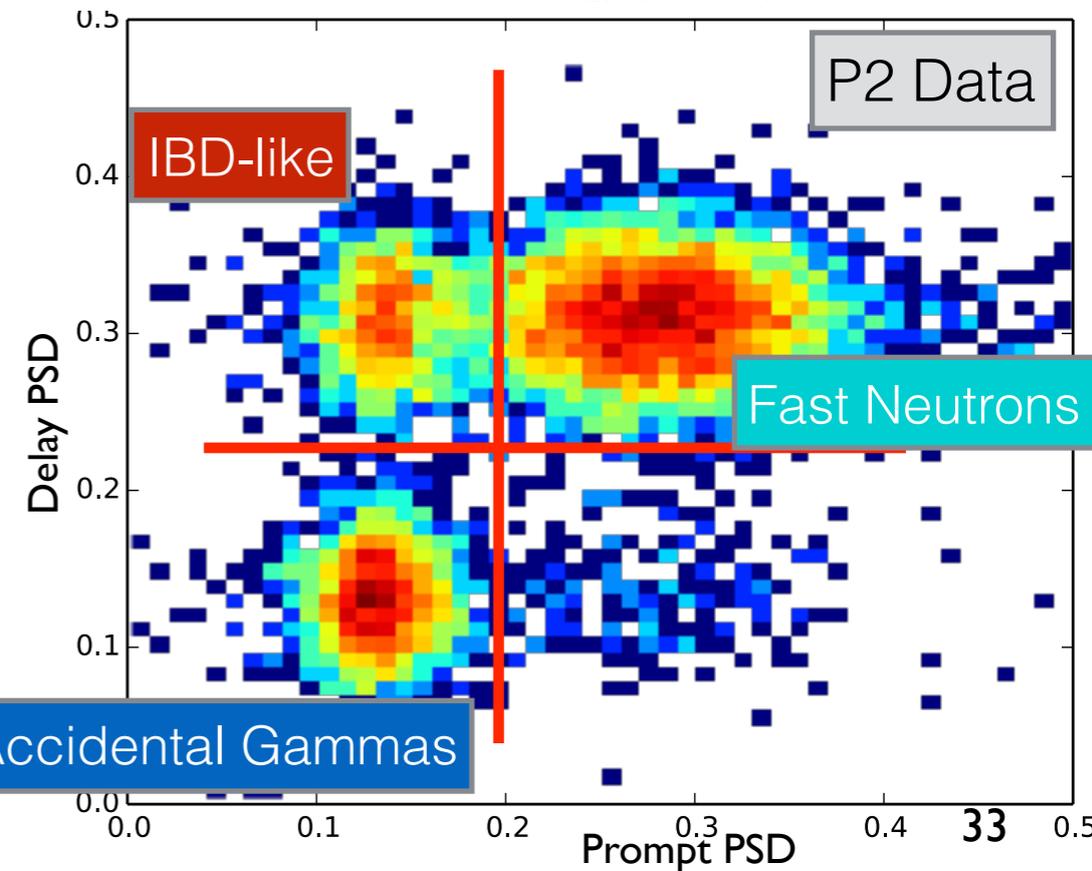
$\gamma$ -like prompt, n-like delay

Fast Neutron

~~n-like prompt, n-like delay~~

Accidentals

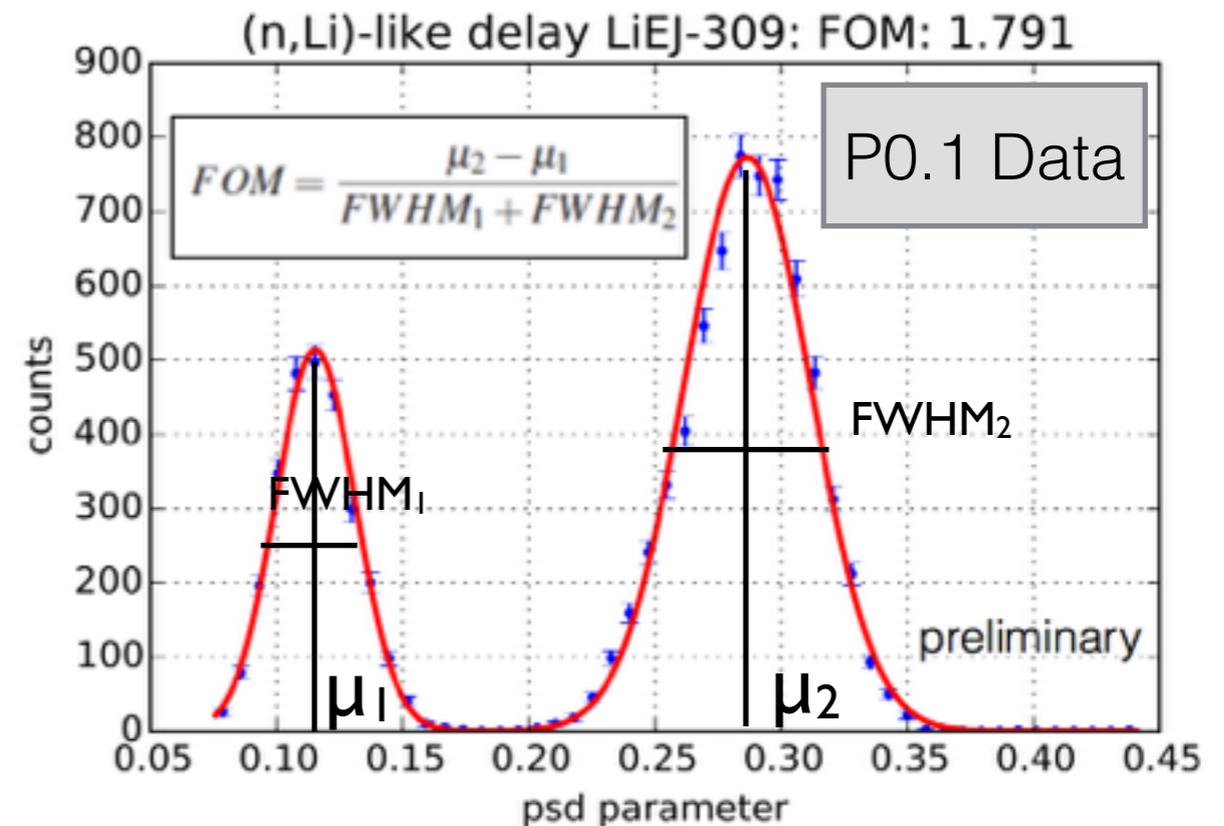
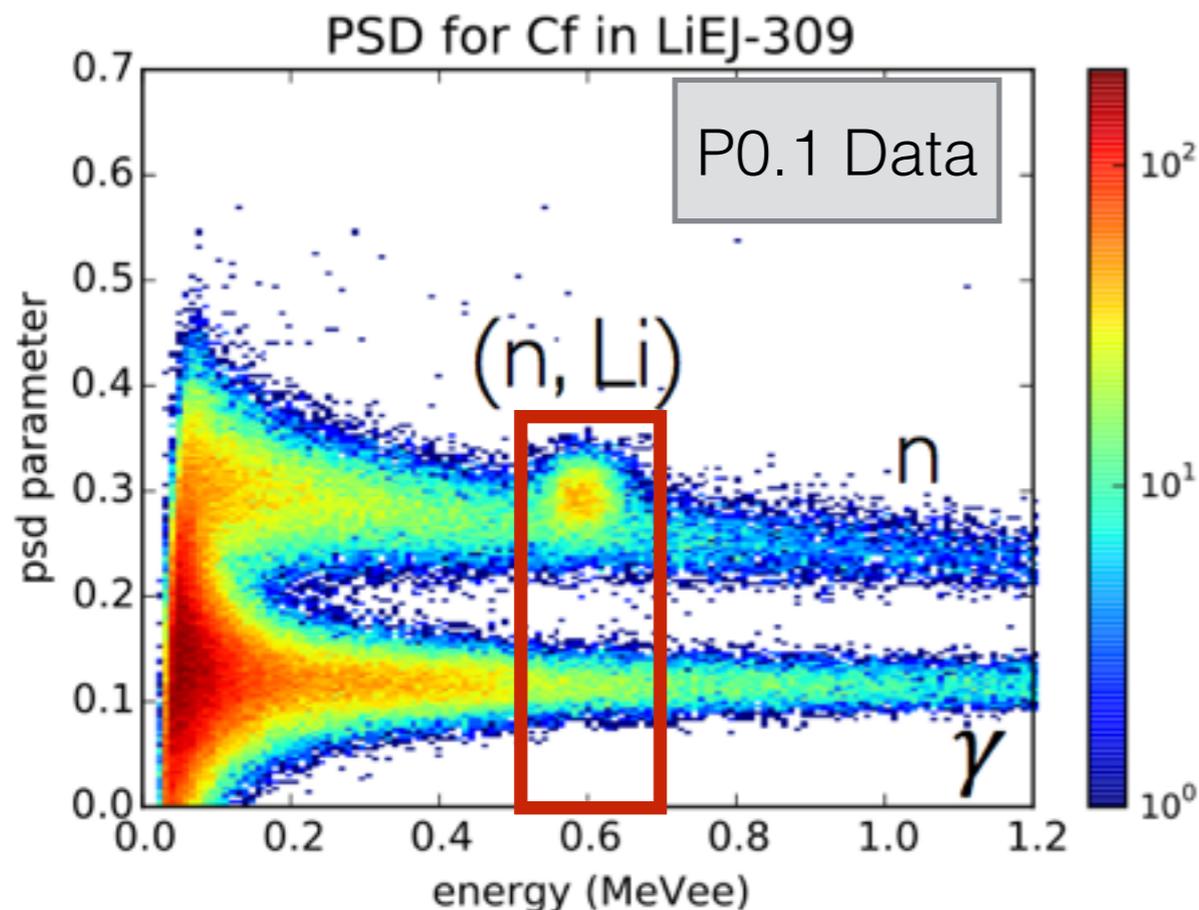
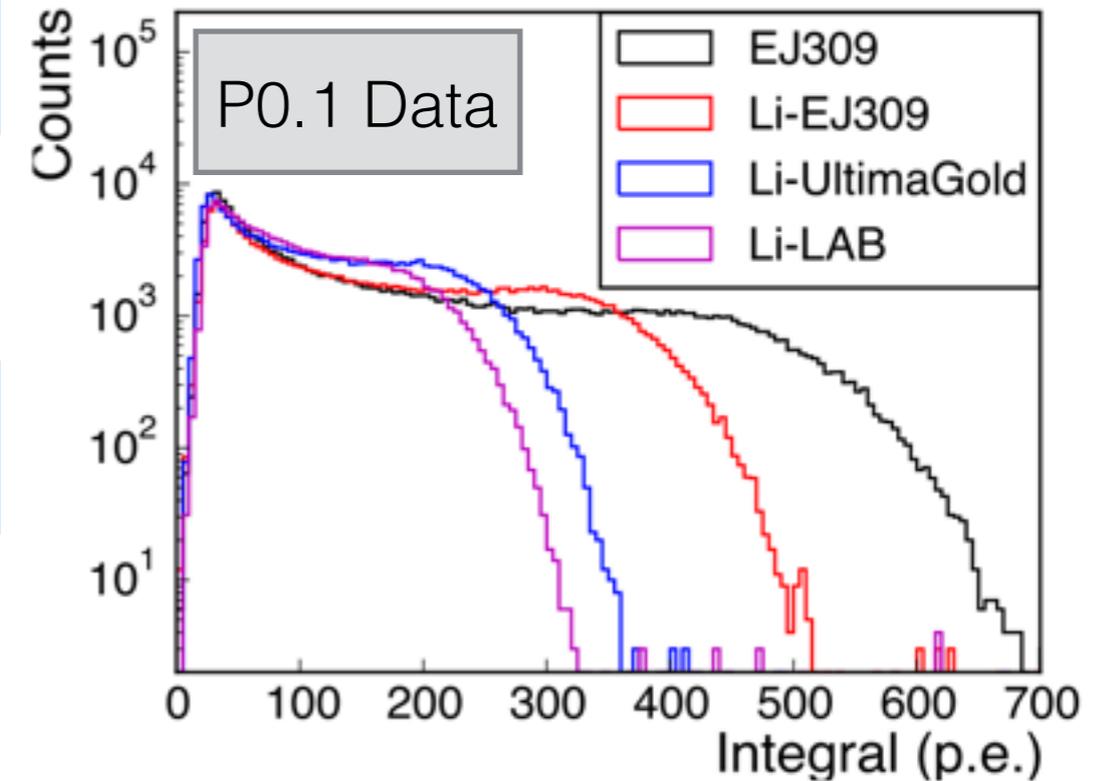
~~$\gamma$ -like prompt,  $\gamma$ -like delay~~



# Background Rejection: Li-EJ309 in P0.1



- Light yield remains high for Li-EJ309
  - 8200 photons/MeV (11500 for EJ309)
  - Needed to meet resolution requirements
- PSD excellent for Li-EJ309
  - Needed for background rejection requirements

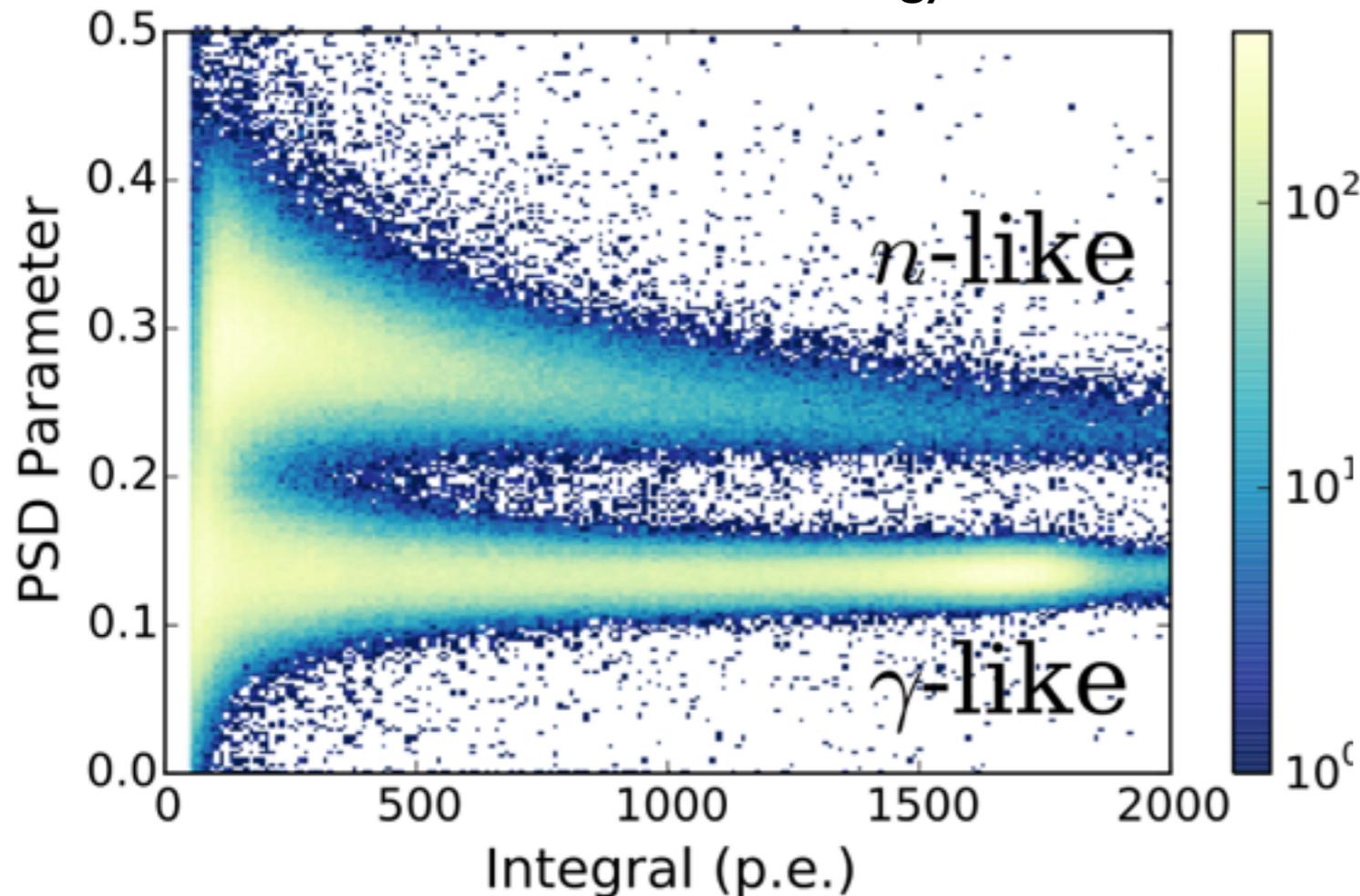


# Background Rejection: PSD in P20

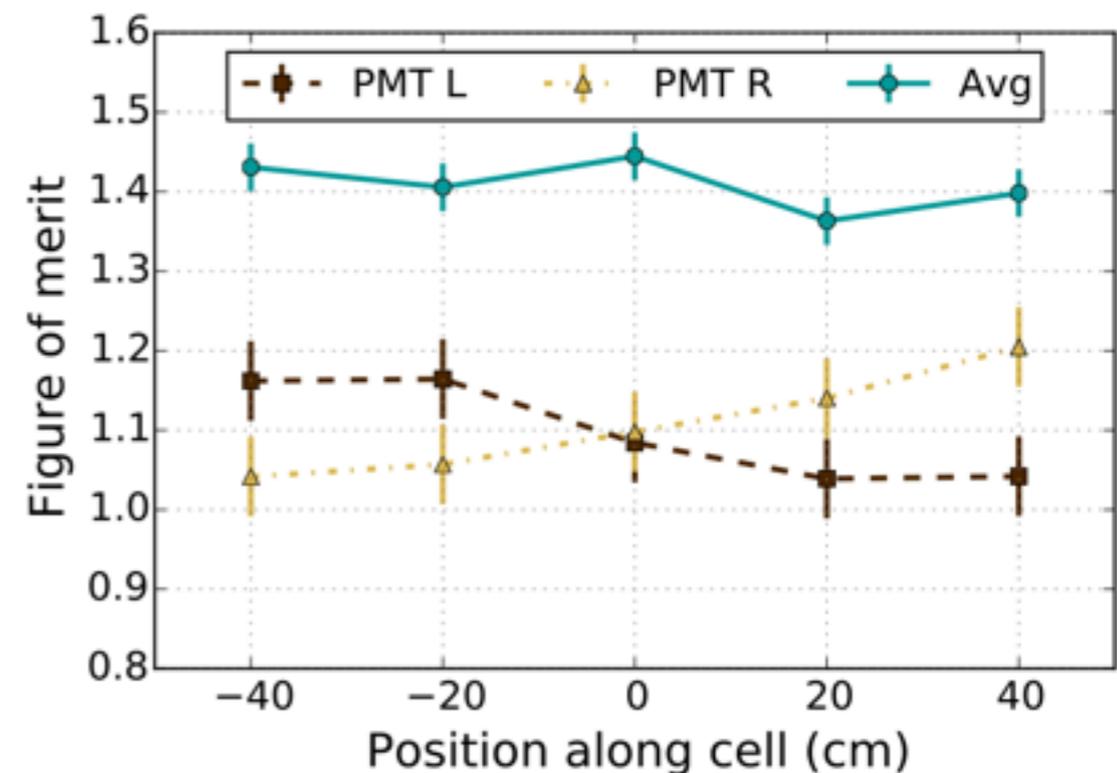
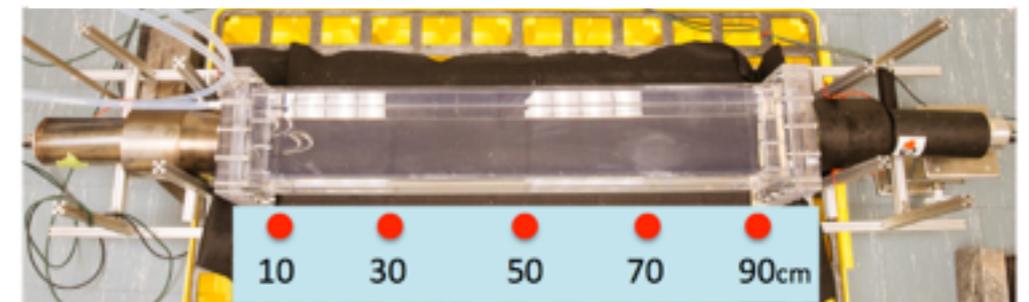


- PSD is maintained even at large cell sizes
  - Ability to reject many neutron-related, reactor gamma backgrounds
  - PSD highly uniform over entirety of meter-length cell

P20, PSD Versus Energy



P20 PSD Response to Cf-252 source

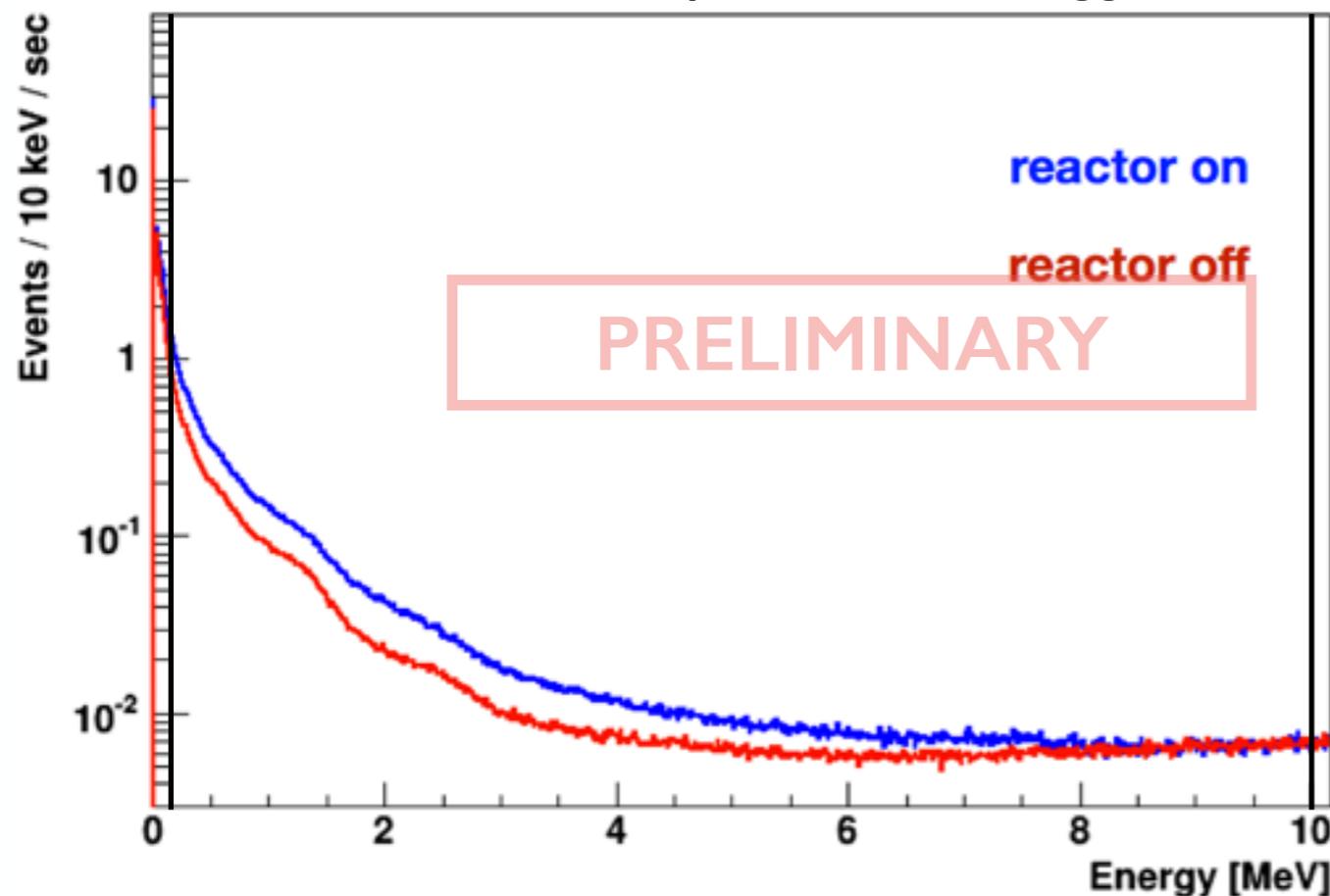


# Background Rejection: Reactor-On

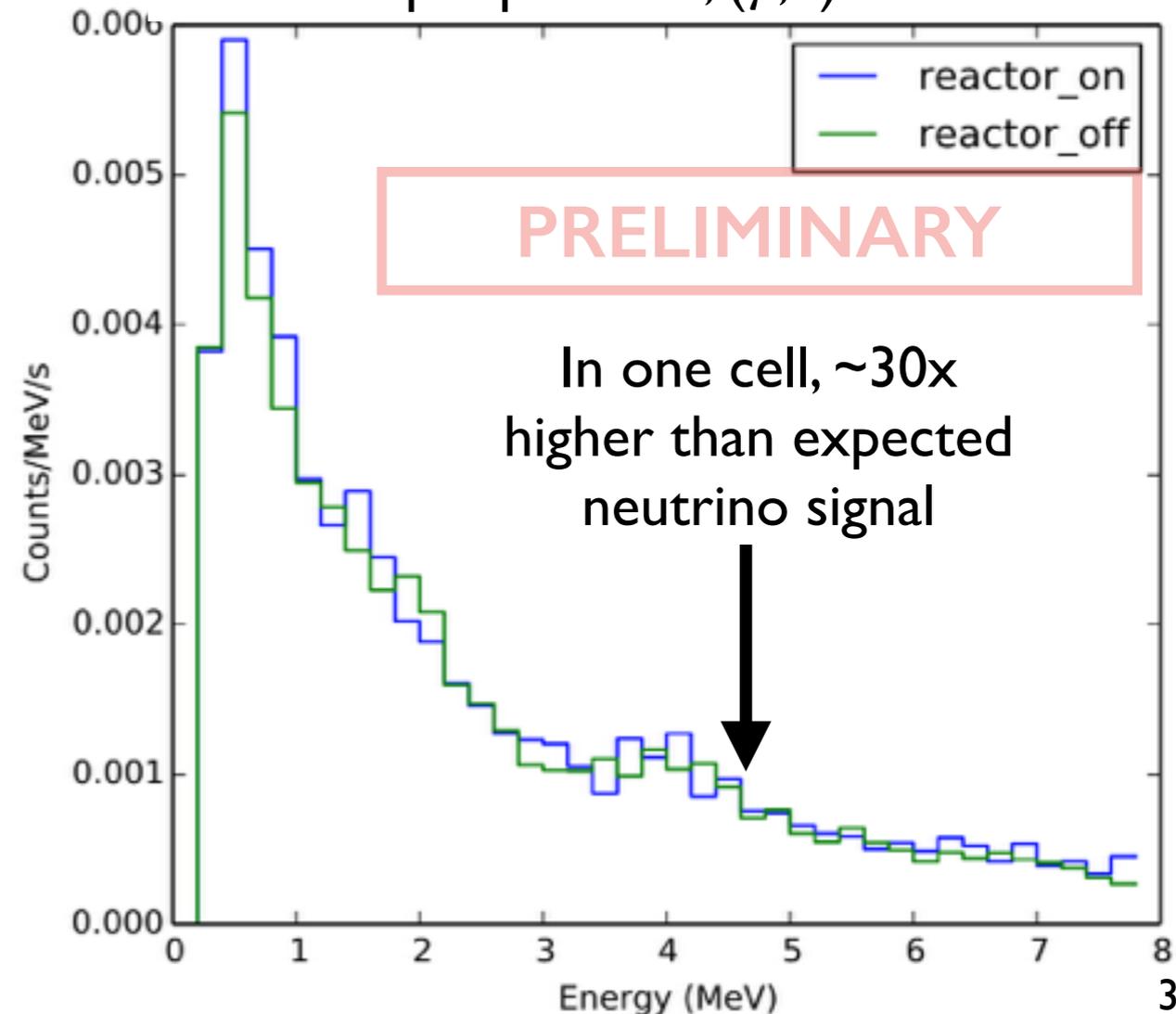


- Sub-dominant change in raw trigger rate with reactor status
- Sub-dominant  $(\gamma, n)$  coincidence change with reactor status
- **Cosmogenic, not reactor backgrounds are the primary concern!**
  - Muon veto says neutrons, not muons, are primary concern!
  - Reactor-off periods very valuable!

PROSPECT20 Spectrum, All Triggers



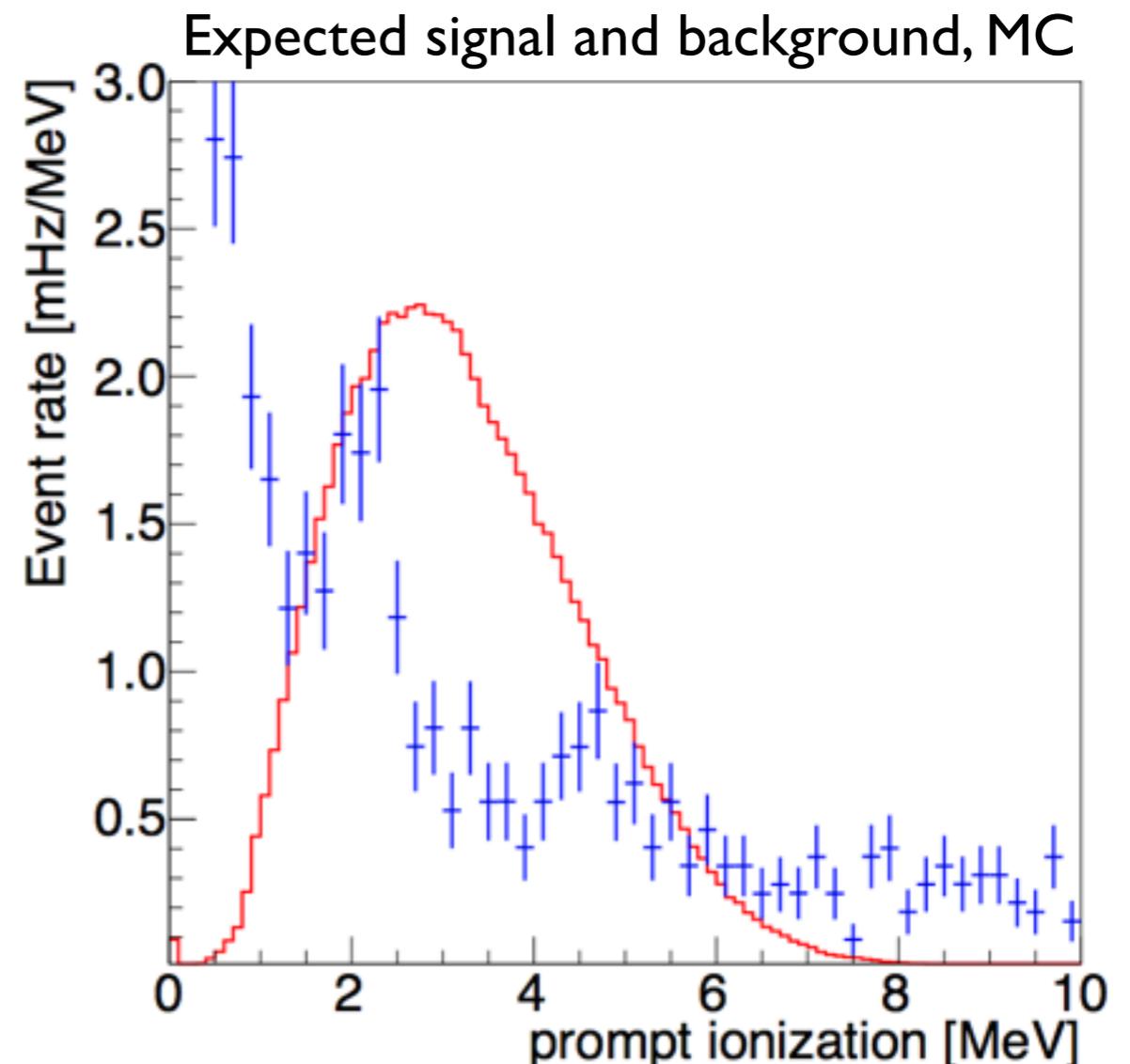
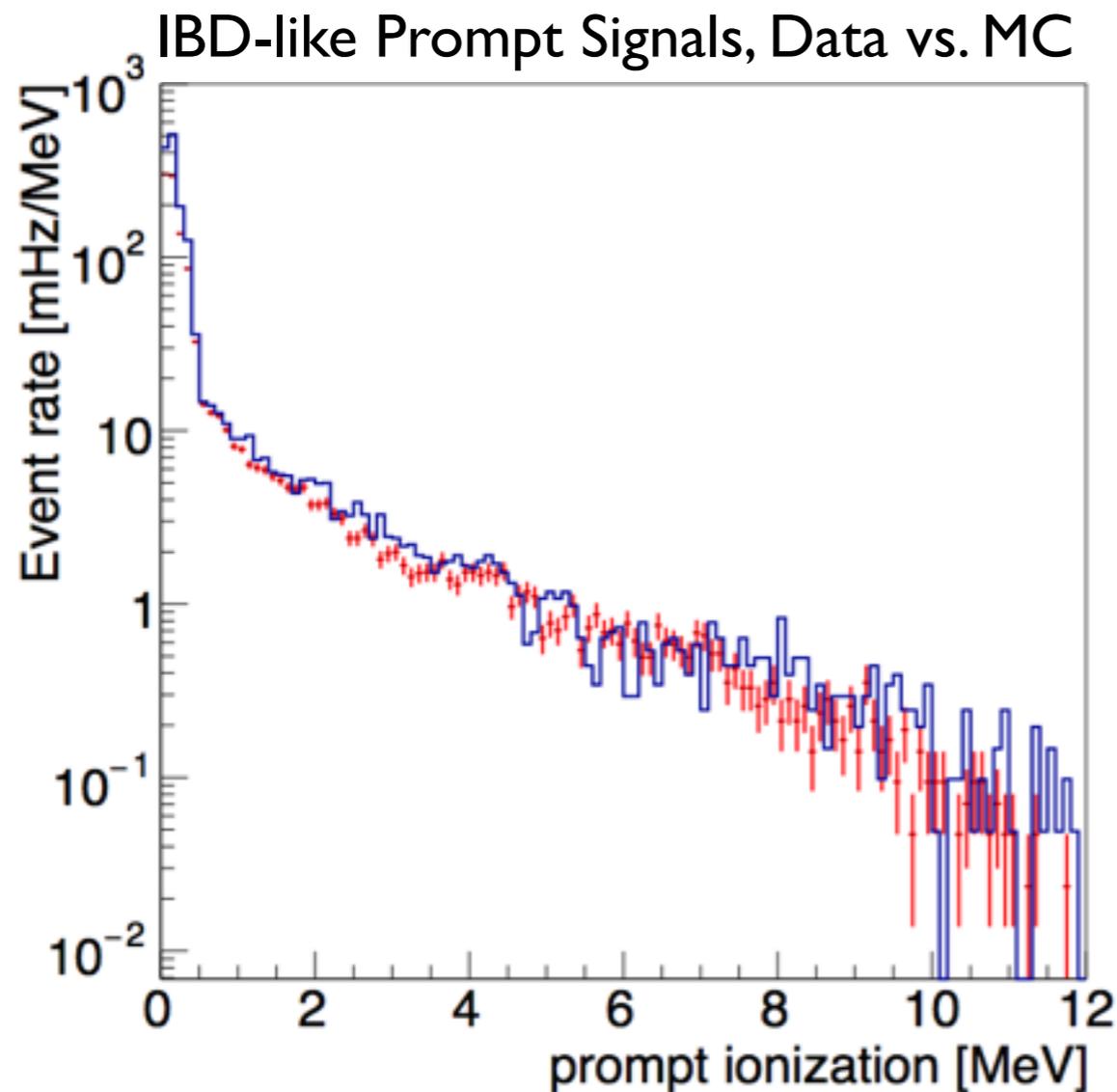
P20 Prompt Spectrum,  $(\gamma, n)$  Coincidences



# Background Estimation: MC/Data Agreement



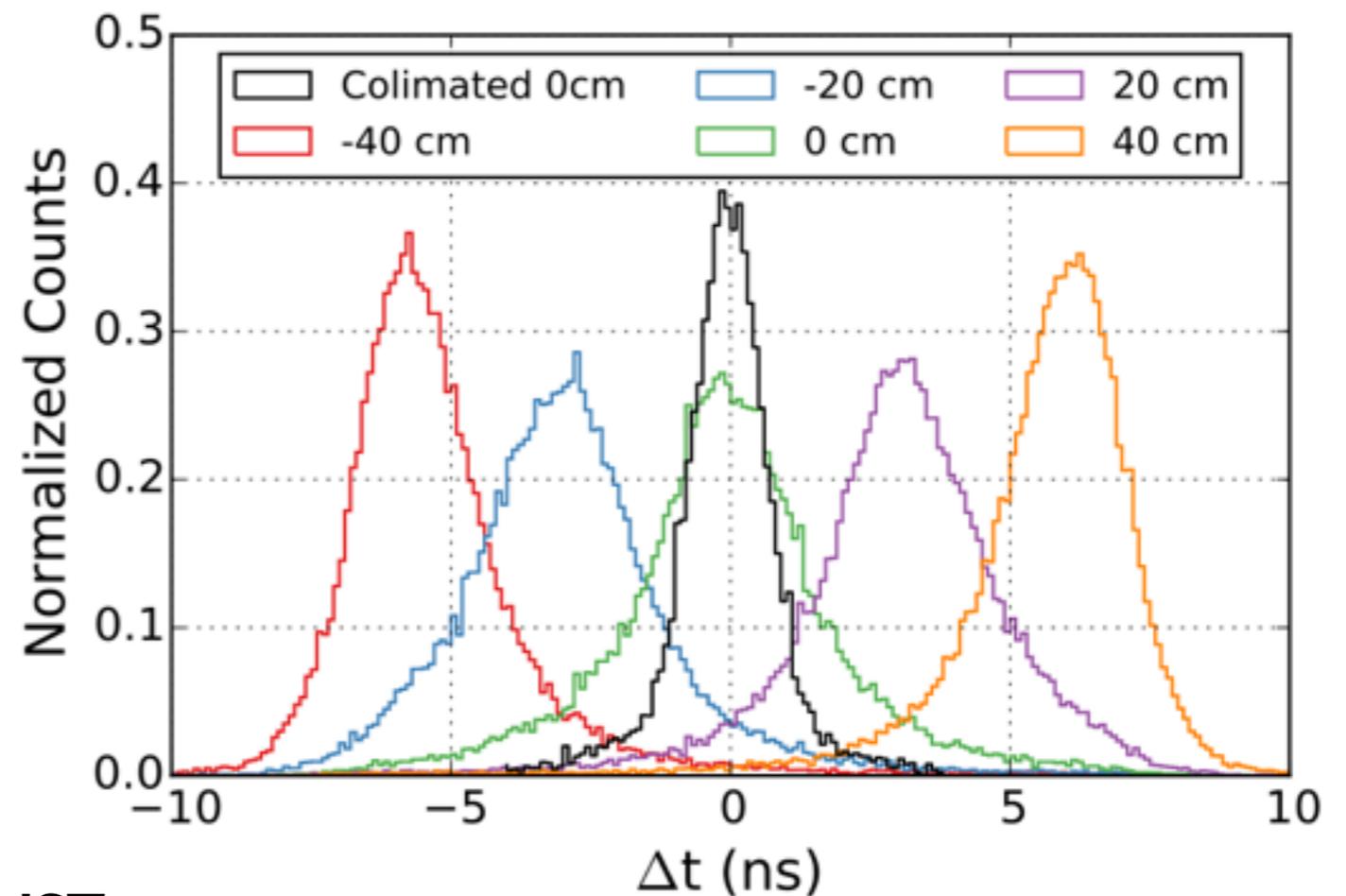
- Have CRY- and Goldhagen-based cosmogenic neutron, muon sim
- **P20 n-coincidences, multiplicity in good agreement with MC**
  - Provides confidence in full PROSPECT S:B estimate from data-matched MC
  - Full PROSPECT topological, multiplicity cuts modeled w/ MC give major power to improve S:B



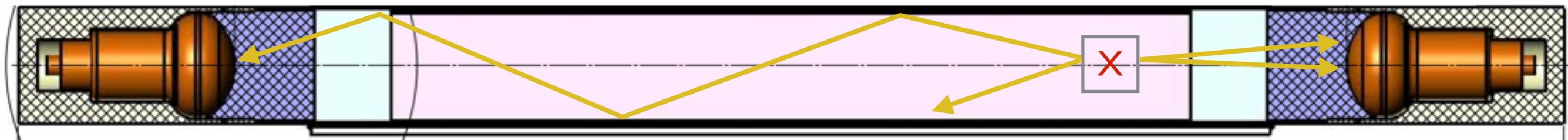
# P20 Demonstration: Position Reco



- Examine charge, arrival time ratios between cell's PMTs
  - Closer PMT to interaction will have more charge, shorter time
- Resolution along cell better than 10cm along cell
  - More topology background rejection capability than we were expecting!
- Segmentation gives resolution in other two dimensions



arXiv:1508.56575 (2015), accepted to JINST

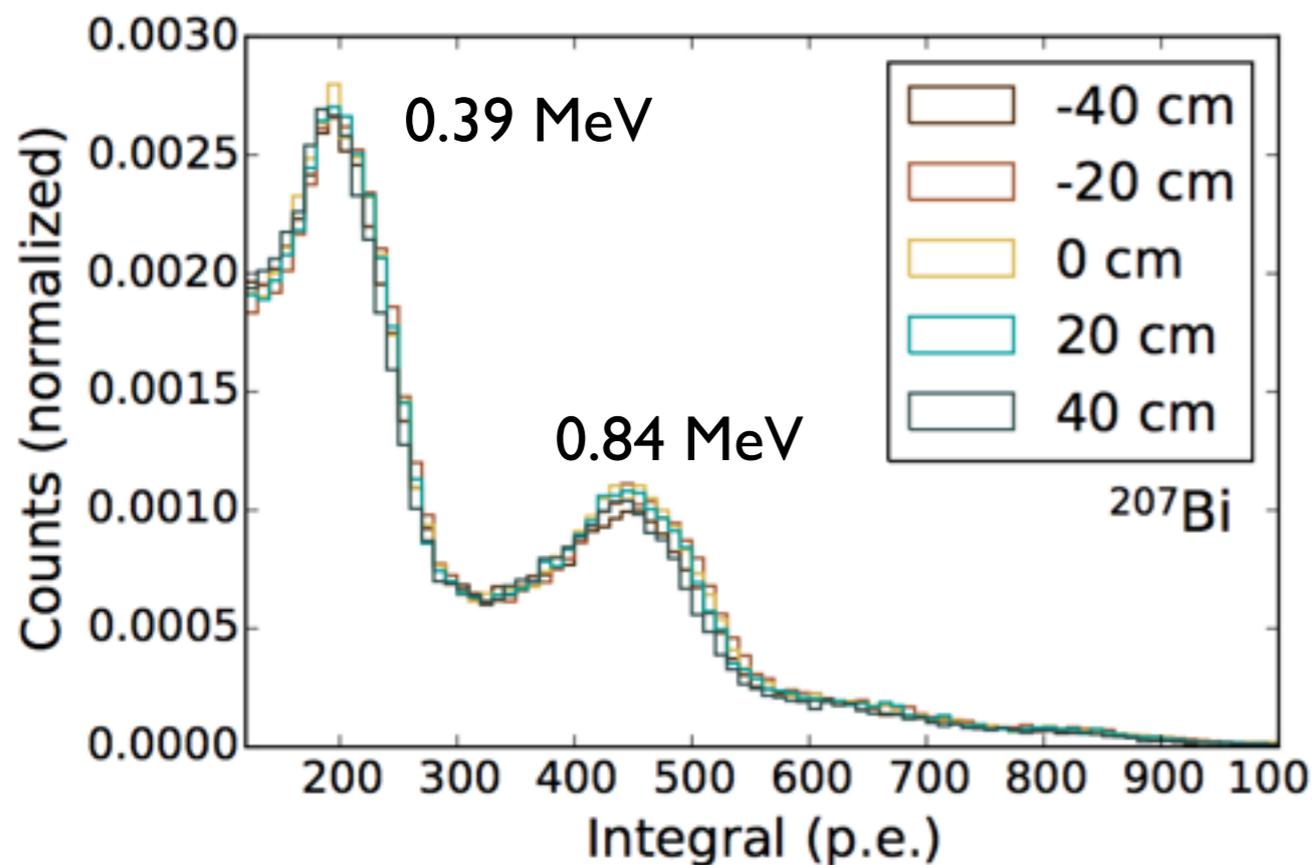


# P20 Demonstration: Energy Response

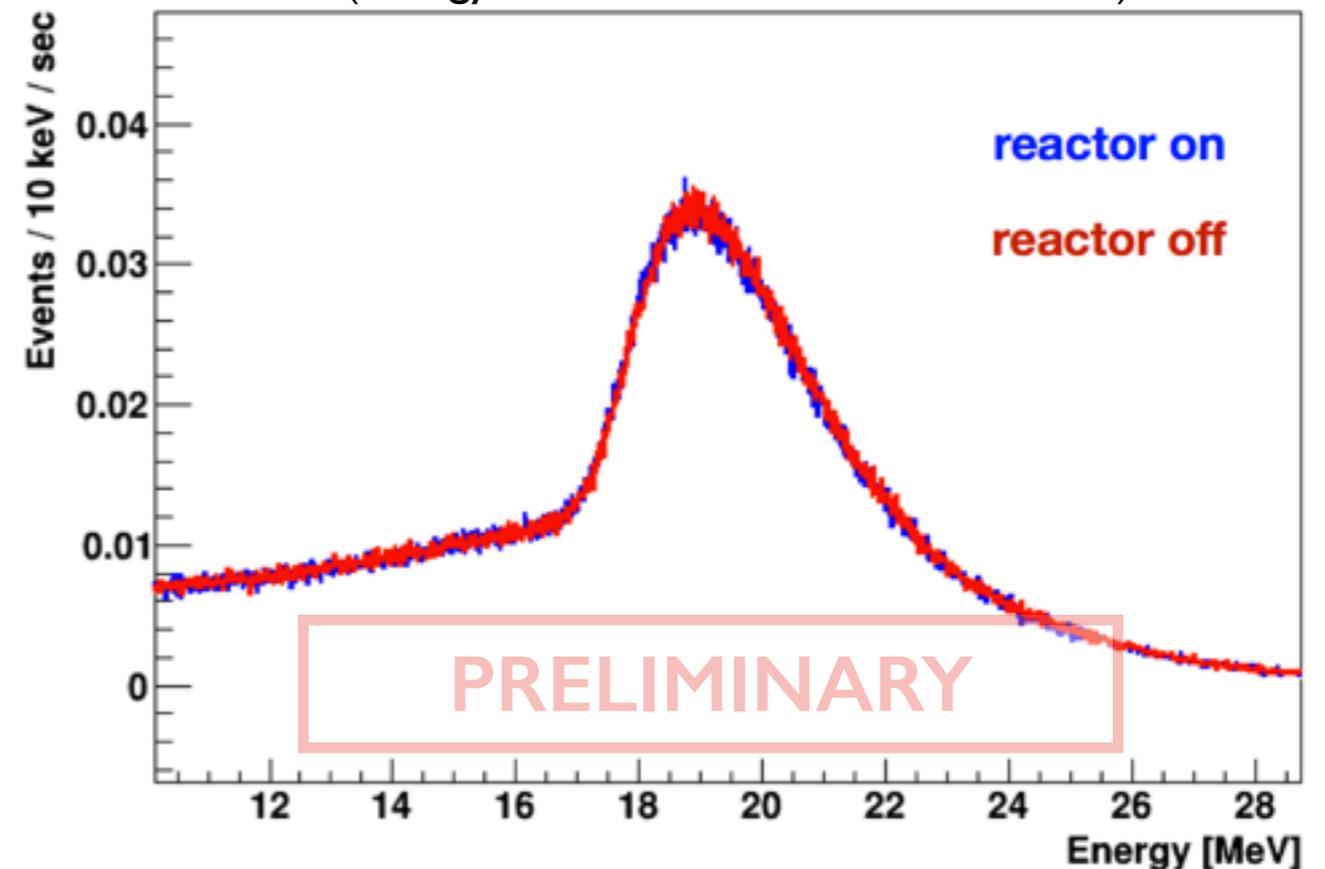


- High, uniform, and stable light collection in full cell
  - Exact PE yield is likely to be different in full PROSPECT cells
- Good energy resolution visible: 4-5% at 1 MeV!
- Many background peaks, calibration sources to choose from

PROSPECT20 Response to Bi-207



Muon MIP Peak in PROSPECT20  
(Energy reduced from FADC saturation)



# Outline

---



- Intro: Reactor  $\bar{\nu}_e$  Flux and Spectrum Predictions
- Reactor Anomaly and recent flux/spectrum measurements
- Future measurement of the  $\bar{\nu}_e$  spectrum at PROSPECT
- **Current context for PROSPECT**

# SBL Reactor Context



- **PROSPECT**: designed to provide a precision measurement for **BOTH** key physics goals
  - Moveable segmented detectors give best mapping of oscillation space
  - Design enables higher energy resolution other efforts
- **PROSPECT** has the experience, development, and infrastructure in place for the world's pre-eminent SBL reactor effort.

My (biased) overview of global efforts — **Good** : **Not Good**

	<u>Effort</u>	Dopant	Good X-Res	Good E-Res	L Range (meters)	Fuel	Exposure, MW*ton	Move-able?	Running at intended reactor?
<b>US</b>	<b>PROSPECT</b>	<b>Li</b>	<b>Yes</b>	<b>Yes</b>	<b>6.5-20</b>	<b>HEU</b>	<b>185</b>	<b>Yes</b>	<b>Yes</b>
	NuLat	Li/B	Yes	Yes	TBD	TBD	TBD	Yes	No
<b>EU</b>	Nucifer	Gd	No	Yes	7	HEU	56	No	Yes
	STEREO	Gd	Yes	Yes	9-11	HEU	100	No	Yes
	SoLid	Li	Yes	No	6-8	HEU	155	No	Yes
<b>Russia</b>	DANSS	Gd	Yes	No	9.7-12	LEU	2700	Yes	Yes
	Neutrino4	Gd	Yes	No	6-12	HEU	150	Yes	Yes
<b>Asia</b>	Hanaro	Li/Gd	No	Yes	20-ish	LEU	30	No	No



- PROSPECT complimentary to current experimental efforts

arxiv:1503.06637  
WINP 2015

## The Intermediate Neutrino Program

### 2.1 Sterile Neutrinos

The working group's consensus can be summarized in the following five recommendations:

3. Experiments designed to test both the  $\nu_\mu$  to  $\nu_e$  appearance and  $\nu_e$  disappearance channels are needed. We must ensure that any pion decay beam program has optimized  $\nu_\mu$  disappearance sensitivity.

# Sterile Oscillation Context



- PROSPECT complimentary to current experimental efforts
  - Independently attacking similar suggested space for each accessible channel
  - Want (need?) signals in all channels to really trust a sterile discovery

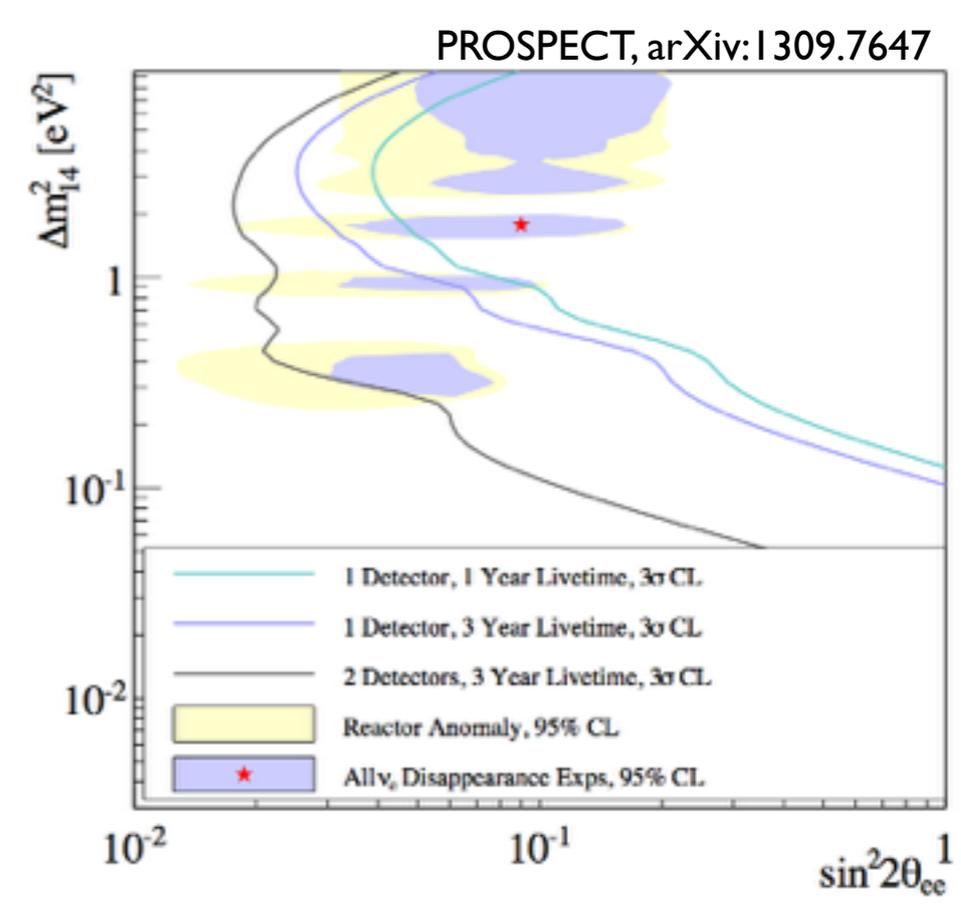
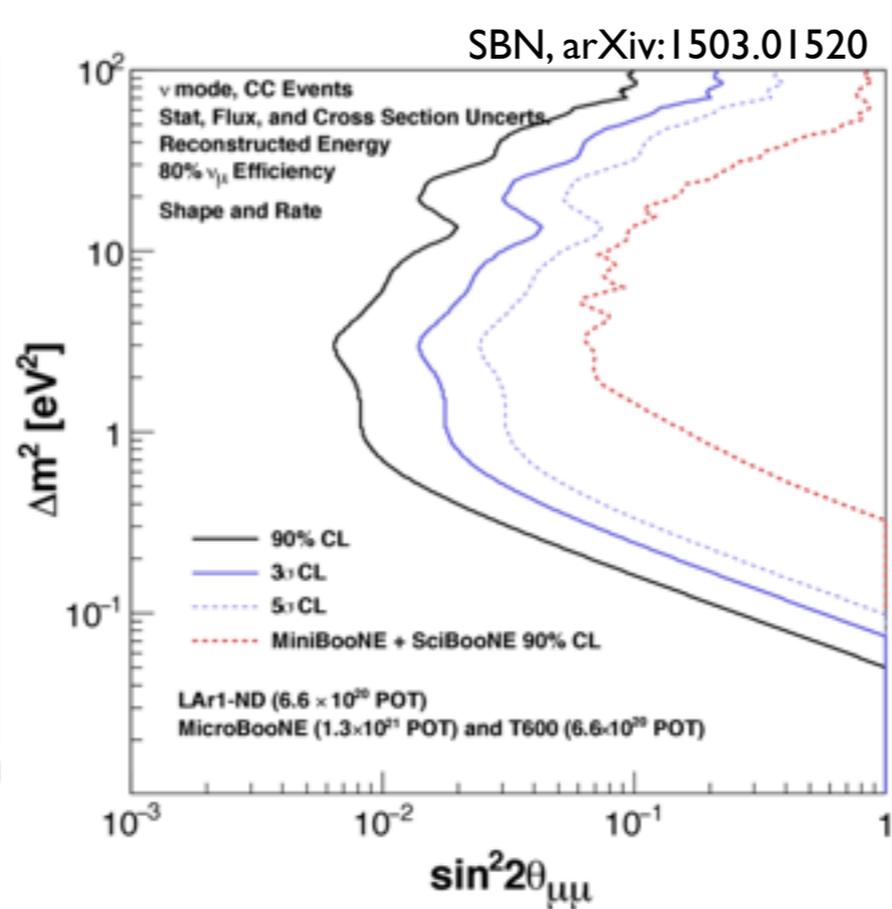
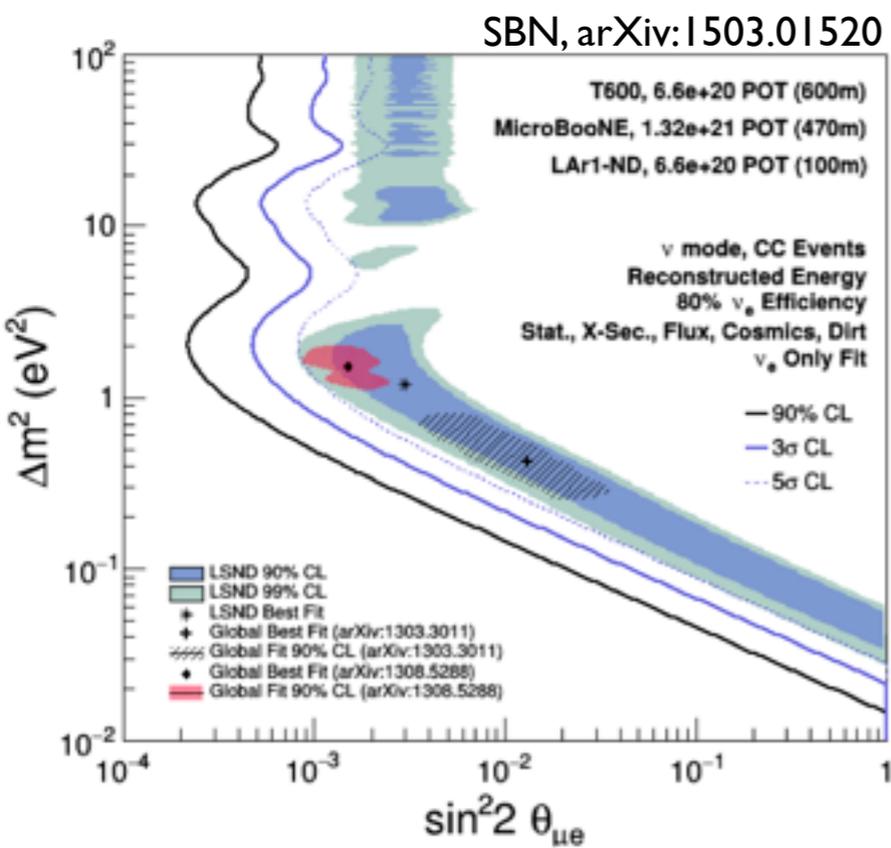
arxiv:1503.06637  
WINP 2015

## The Intermediate Neutrino Program

### 2.1 Sterile Neutrinos

The working group's consensus can be summarized in the following five recommendations:

3. Experiments designed to test both the  $\nu_\mu$  to  $\nu_e$  appearance and  $\nu_e$  disappearance channels are needed. We must ensure that any pion decay beam program has optimized  $\nu_\mu$  disappearance sensitivity.



# Summary



- Much has been learned about the absolute reactor  $\bar{\nu}_e$  flux and spectrum in the past 2-3 years
- More data is needed to address persisting questions
- PROSPECT will provide valuable new SBL  $^{235}\text{U}$   $\bar{\nu}_e$  data
  - Can address existing sterile best-fits with <1 calendar year of data
  - Reactor  $\bar{\nu}_e$  disappearance complimentary to SBN program ( $\nu_e$  app,  $\nu_\mu$  dis)
  - Learn much about reactor spectrum regardless of oscillation outcome
- Prototype deployments at HFIR are well underway
  - Two new papers demonstrate backgrounds and detector response
  - Well-prepared for efficient assembly and deployment of the full experiment



---

END

# PROSPECT Physics: Absolute Spectrum

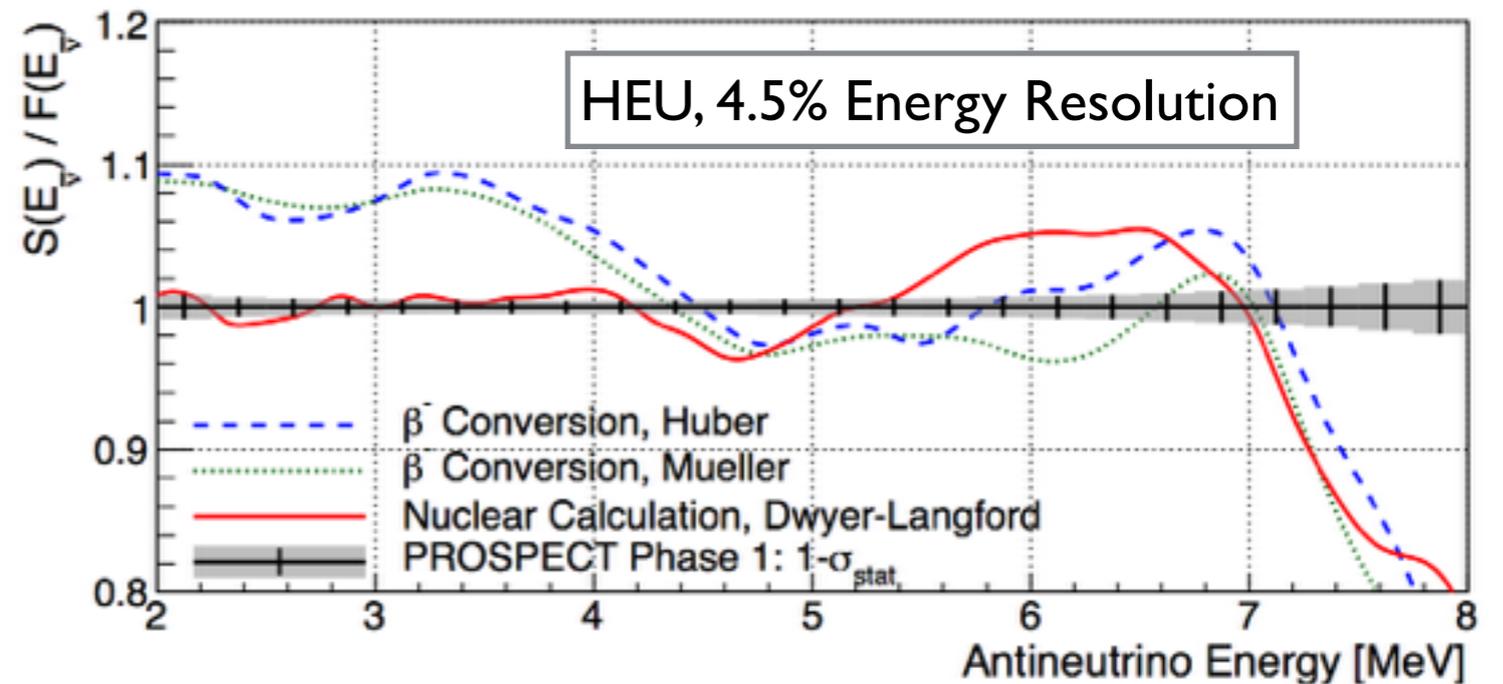
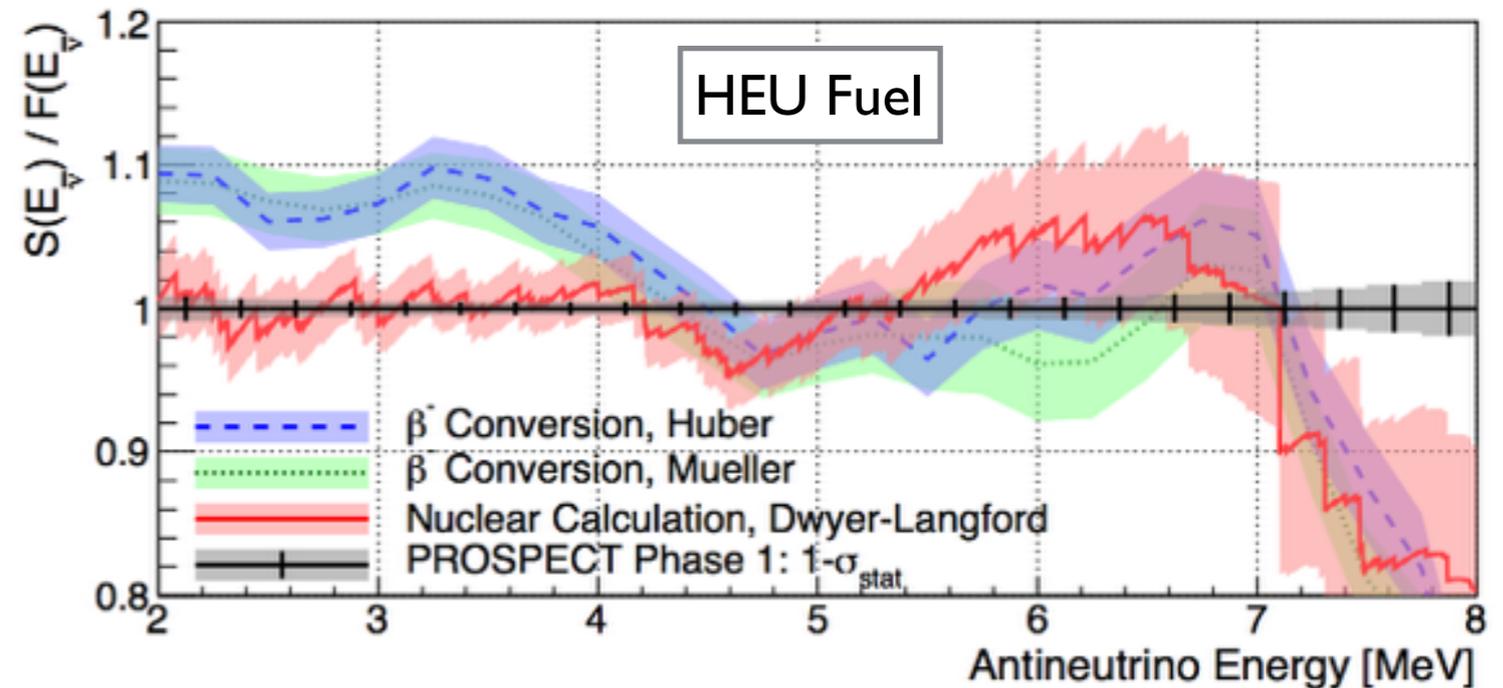


- How much fine structure exists in reactor spectrum?

- Ab initio calculations suggest significant fine structure from endpoints of prominent beta branches

- PROSPECT can provide highest-ever energy resolution on the spectrum

- Thus, will give best fine structure measurement
- Goal resolution: 4-5%
- Provide constraints on individual beta branches (reactor spectroscopy)?
- Input for next reactor experiments (JUNO)?



# Reactor Spectrum: Why Do We Care?



- Major implications for Standard Model if  $\nu_s$  DO actually exist

- Even if they do not, ability to constrain reactor  $\bar{\nu}_e$  models

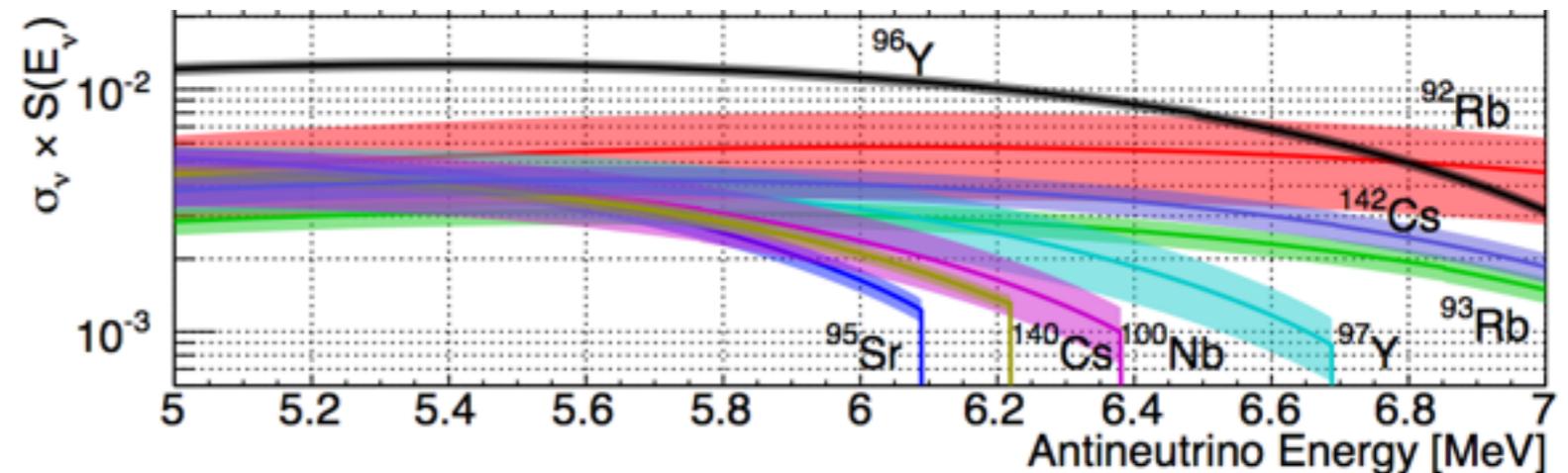
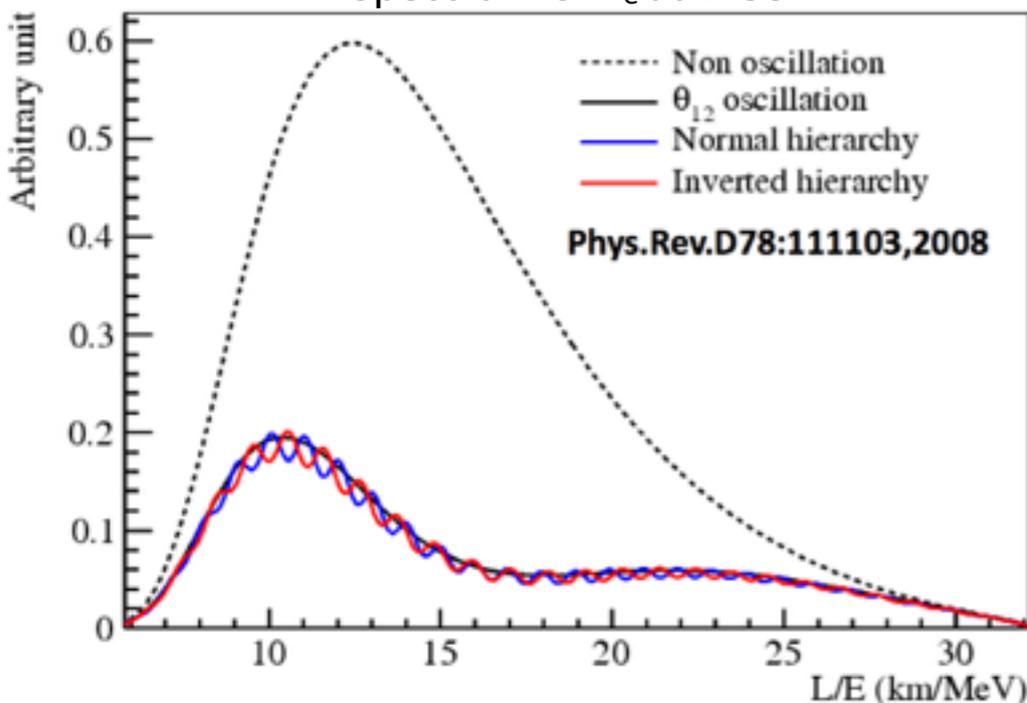
- Valuable for reactor oscillation experiments
- Inputs to reactor modeling
- ‘Reactor spectroscopy:’ probe individual branches in reactor spectrum
- Implications for non-proliferation

Buttons Provided by Neutrino2014!  
Sweater Provided by J. Asaadi



Dwyer and Langford, PRL 114 (2015)

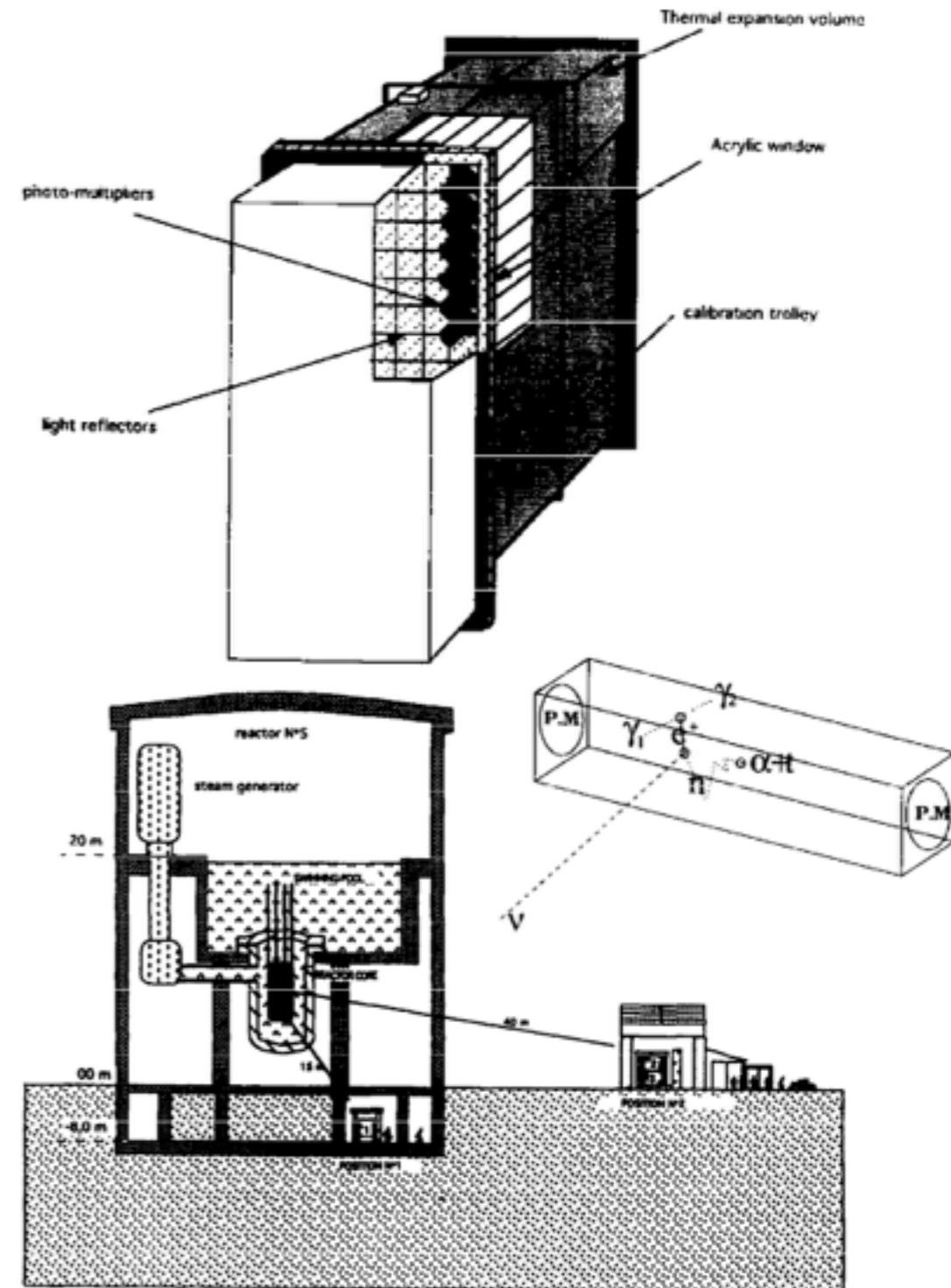
Spectrum of  $\nu_e$  at  $L \sim 53$  km



# Historical Context



- A similar experimental setup in the past: Bugey-3
  - Segmented short-baseline LiLS detector
- PROSPECT Pros:
  - Smaller reactor core, closer to core: better for SBL oscillation search
    - Further improved by cell-to-cell oscillation search
  - Stable scintillator: Bugey's degraded after a few months in near detector!
  - Smaller target dead volume: ~2% versus >15% for Bugey
  - Better light yield, energy resolution
- Only Bugey Pro: Overburden
  - 14+ mwe (Bugey-3), <10 mwe (PROSPECT)
    - Bugey had 25:1 S:B; PROSPECT can be successful with 1:1

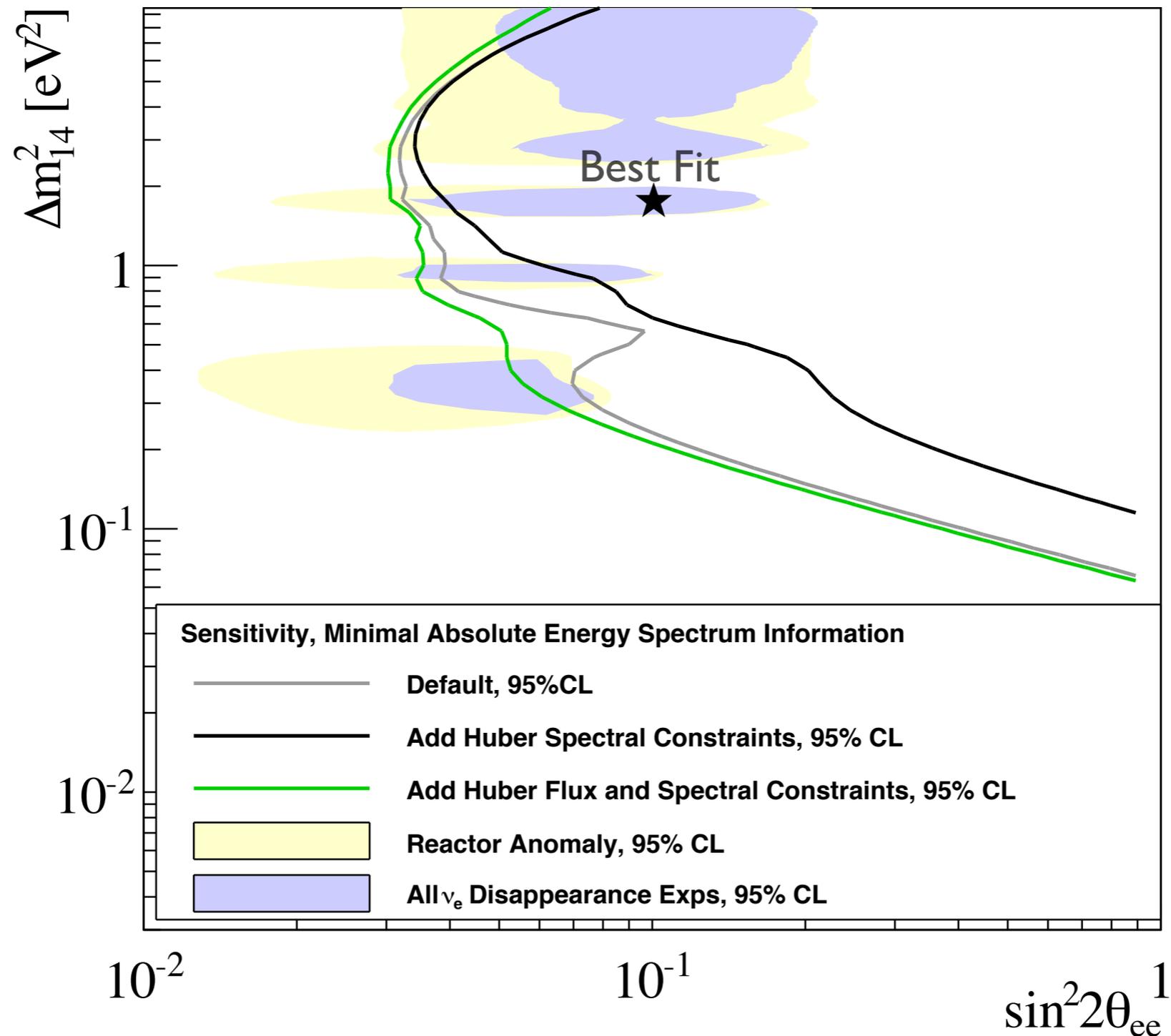


from Abbes et al, NIM A374 (1996)

# Oscillation: Absolute Uncertainties



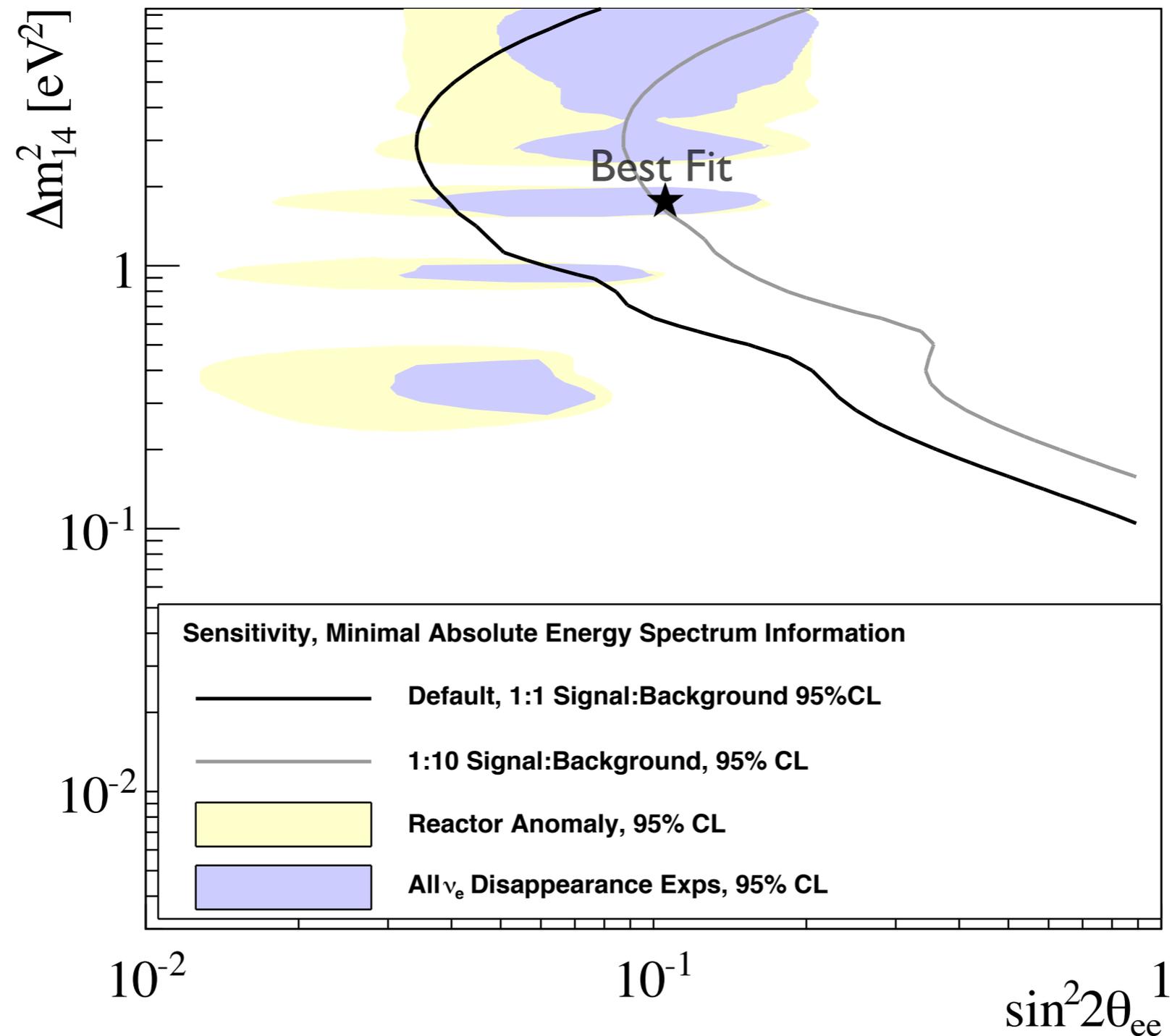
- Oscillations with spectral prediction assumptions included:



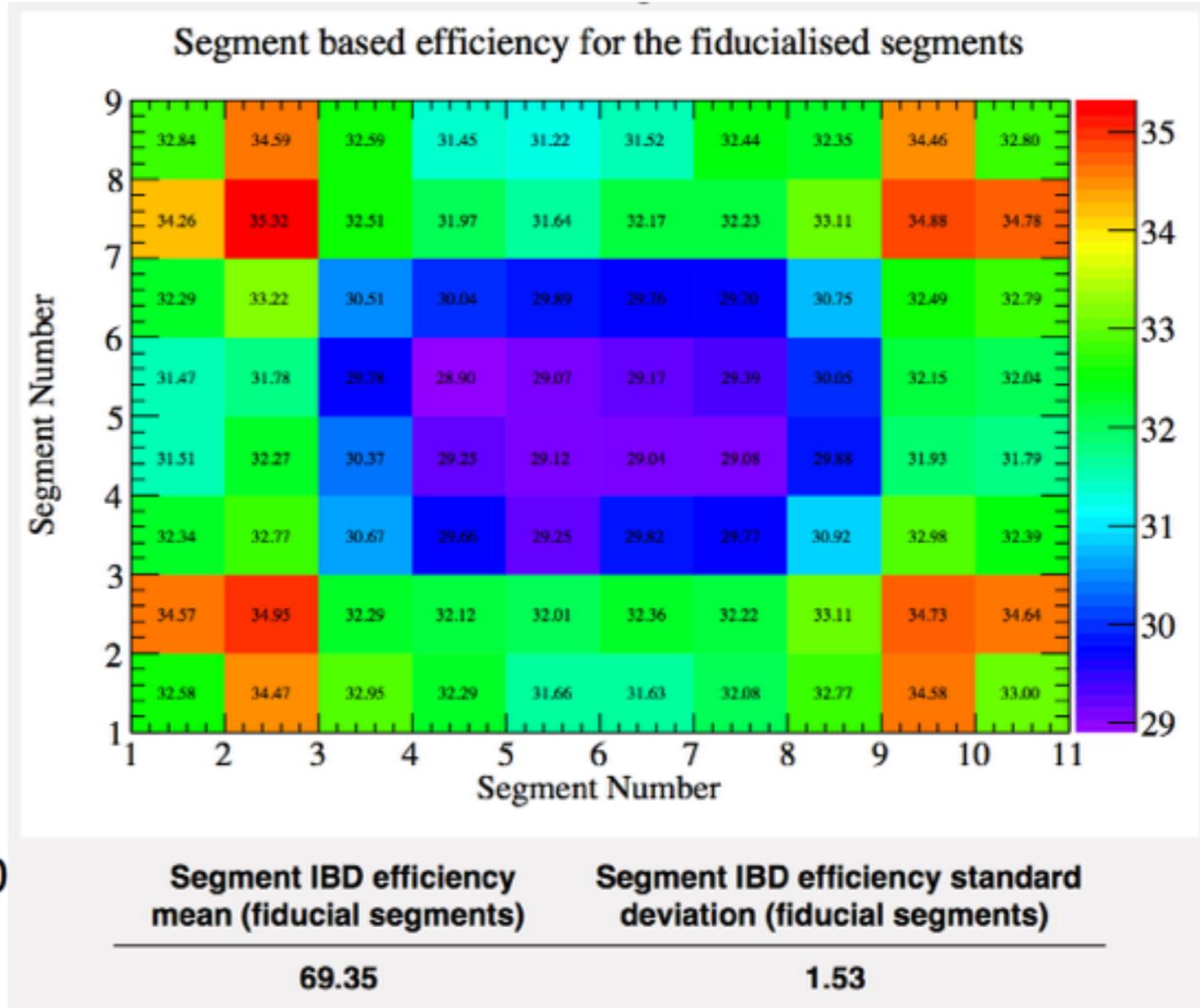
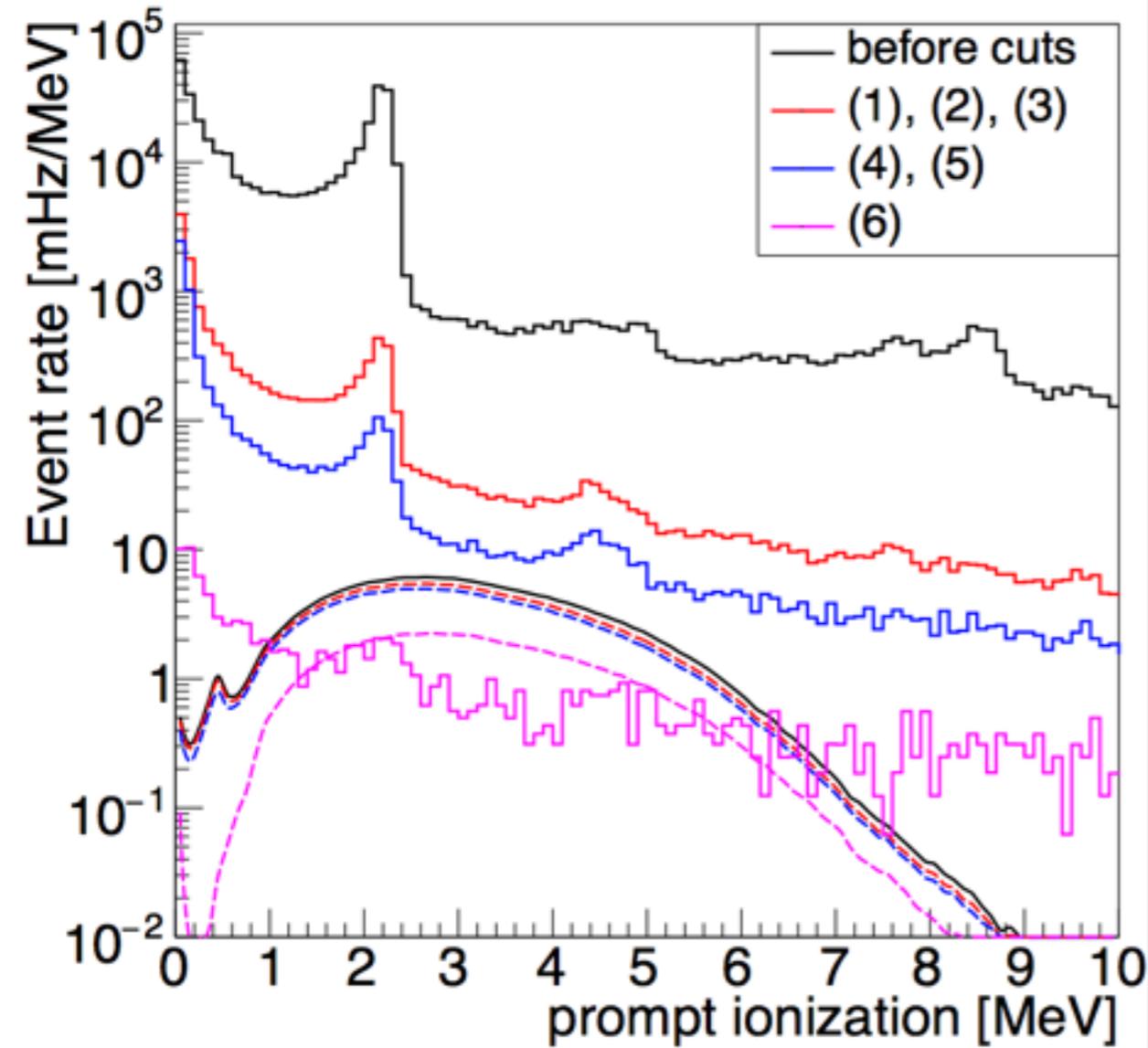
# Oscillation: S:B



- Still have significant osc. sensitivity with 10x larger background



# Efficiencies



# Relative Systematics



- Osc sensitivities include 1.5% totally uncorrelated uncertainty
- Developing covariance matrix approach to include relative cell-to-cell detector, backgrounds systematics more precisely
- Running simulations to quantify cell-to-cell energy response differences
  - How does calibration source signal differ with deployment position?
  - How much is from energy leakage?
  - How much is from as-constructed cell-to-cell variations?
  - How big a cell-to-cell response correction will we need to apply?  
Uncertainties on this correction?



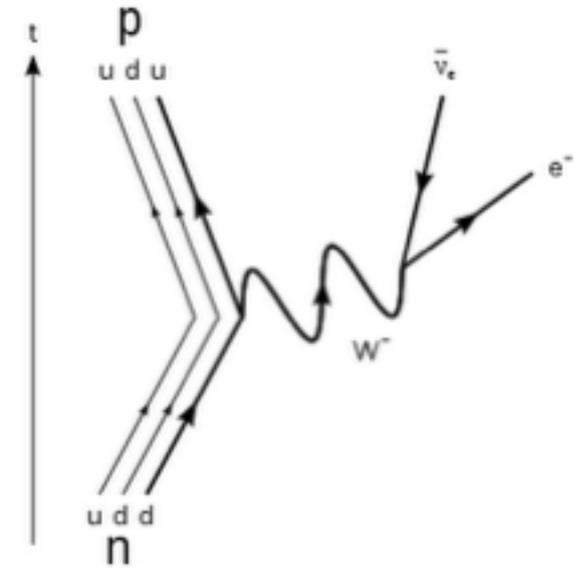
# Beta Decay Recap

- W-mediated weak interaction
- Use Fermi's Golden rule to calculate:

$$N_{\beta}(W) = K \underbrace{p^2(W - W_0)^2}_{\text{phase space}} F(Z, W)$$

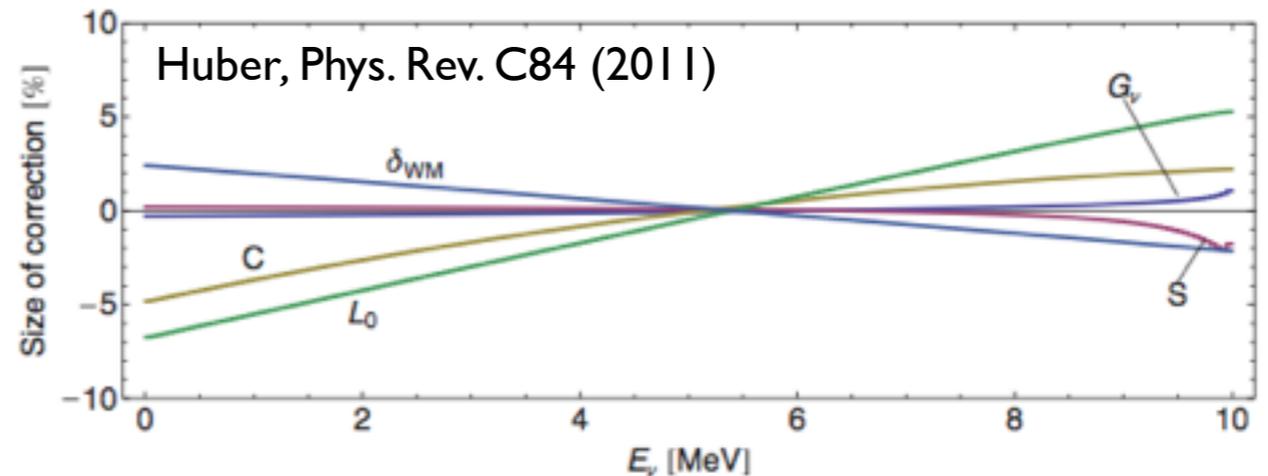
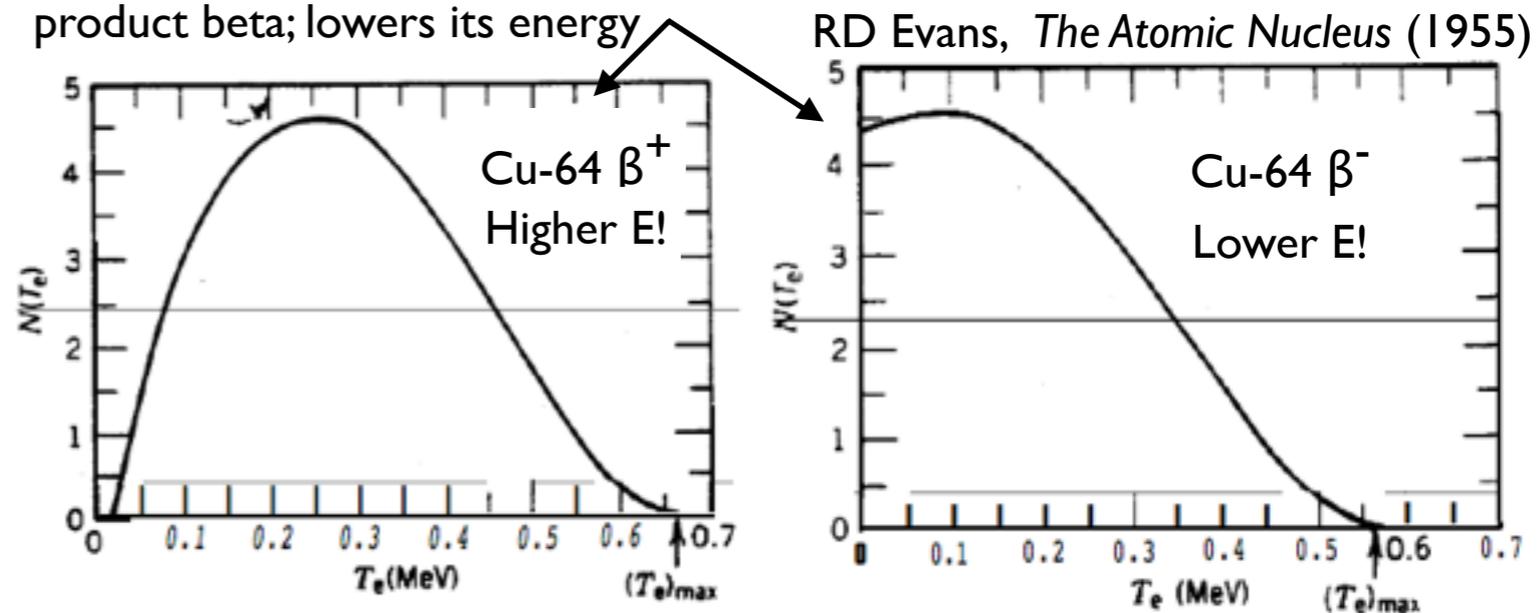
From nuclear matrix element:  
Extra factors of p pop  
in here for beta decays

QED correction: semi-classically,  
positive nucleus attracts  
product beta; lowers its energy



- Other corrections:

- Finite size: C, L<sub>0</sub>
- Electron screening: S
- Radiative corrections: C
- Weak magnetism: d<sub>WM</sub>





# Forbidden Decay Handling

- W-mediated weak interaction
- Use Fermi's Golden rule to calculate

$$N_{\beta}(W) = K \underbrace{p^2(W - W_0)^2}_{\text{phase space}} F(Z, W)$$

From nuclear matrix element:  
Extra factors of  $p$  pop  
in here for beta decays

- Hayes, et. al, PRL 112 (2014):  
conversion result highly  
dependent on forbidden-ness  
of virtual branches

- Capable of shifting predicted  
flux downward by 5%
- Has not been shown what  
forbidden decay treatment  
would reproduce both reactor  
beta and nuebar spectra —  
but it might be possible to do so

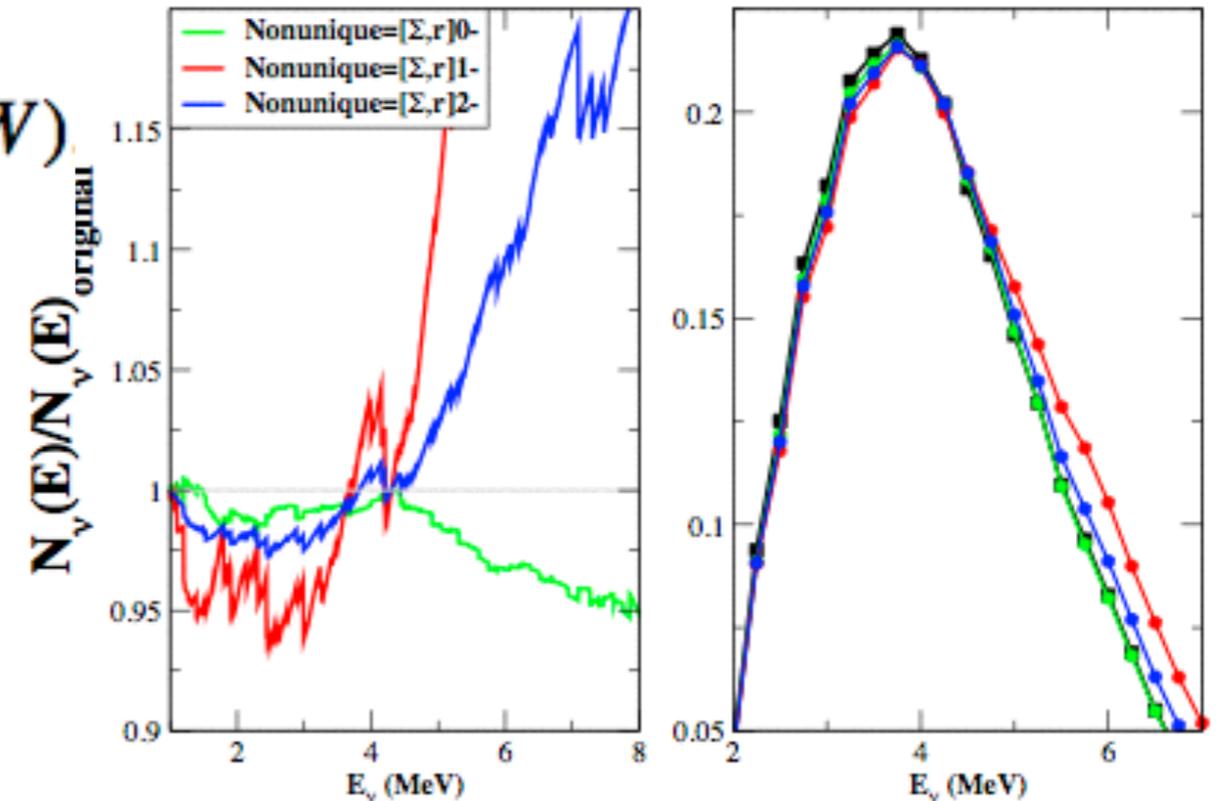


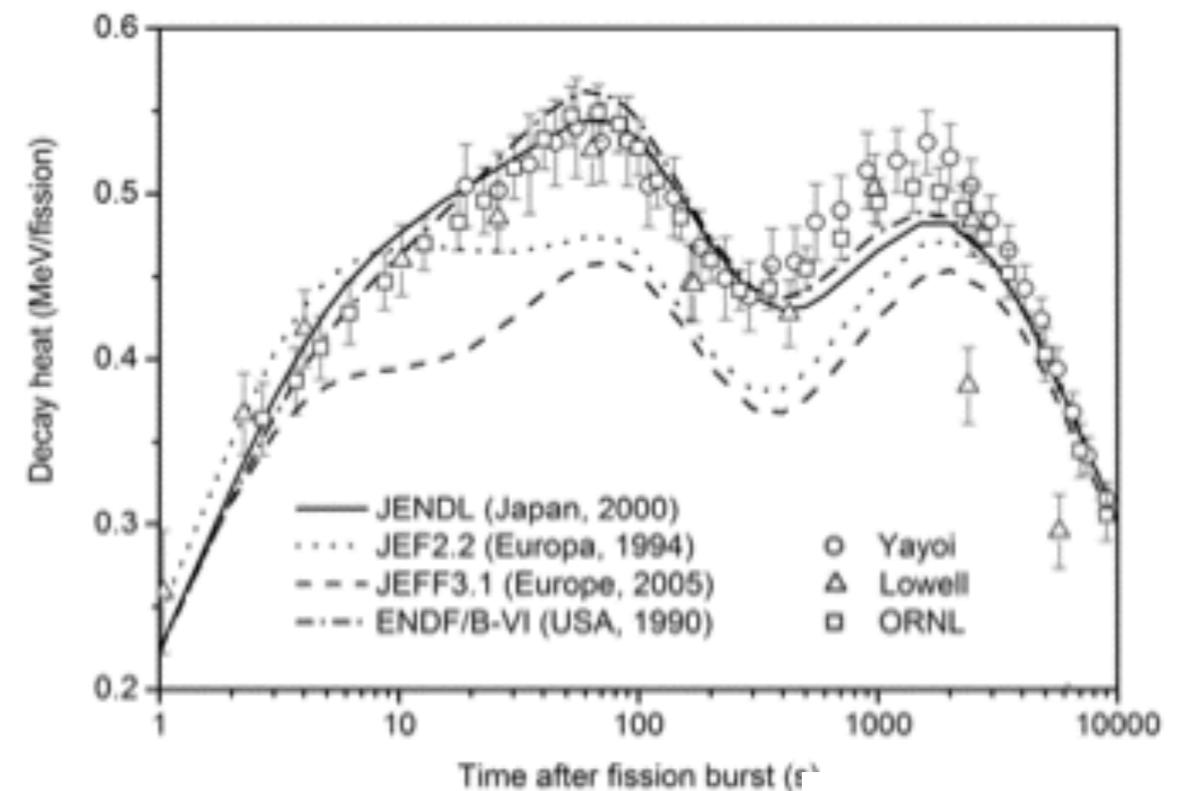
FIG. 3: Different treatments of the forbidden GT transitions contributing to the antineutrino spectrum summed over all actinides in the fission burn in mid-cycle [21] of a typical reactor. The left panel shows the ratio of these antineutrino spectra relative to that using the assumptions of Ref. [4]. The right panel shows the spectra weighted by the detection cross section, where the additional curve in black uses the assumptions of Ref. [4]. The spectra are strongly distorted by the forbidden operators, being lower below the peak and in some cases more than 20% larger above the peak than Ref. [4]. The corresponding change in the number of detectable antineutrinos relative to [4] is -0.75%, 5.8% and 1.85% for the  $0^-$ ,  $1^-$ , and  $2^-$  forbidden operators, respectively.

# Reactor Spectroscopy: Application



- Why is there more decay heat than predicted 3-3000s after a reactor is turned off???
- Means we need higher cooling safety factors during reactor-off periods: This costs \$\$\$!!!
- Hypothesis: maybe we measured branching fractions of some rare isotopes incorrectly...

Figure 3. Electromagnetic decay heat following thermal fission burst of  $^{239}\text{Pu}$  – data from JENDL, JEF-2.2, JEFF-3.1 and ENDF/B-VI are shown together with experimental data from Yayoi, Lowell and Oak Ridge National Laboratory



VOLUME 25

Nuclear Science  
NEA/WPEC-25

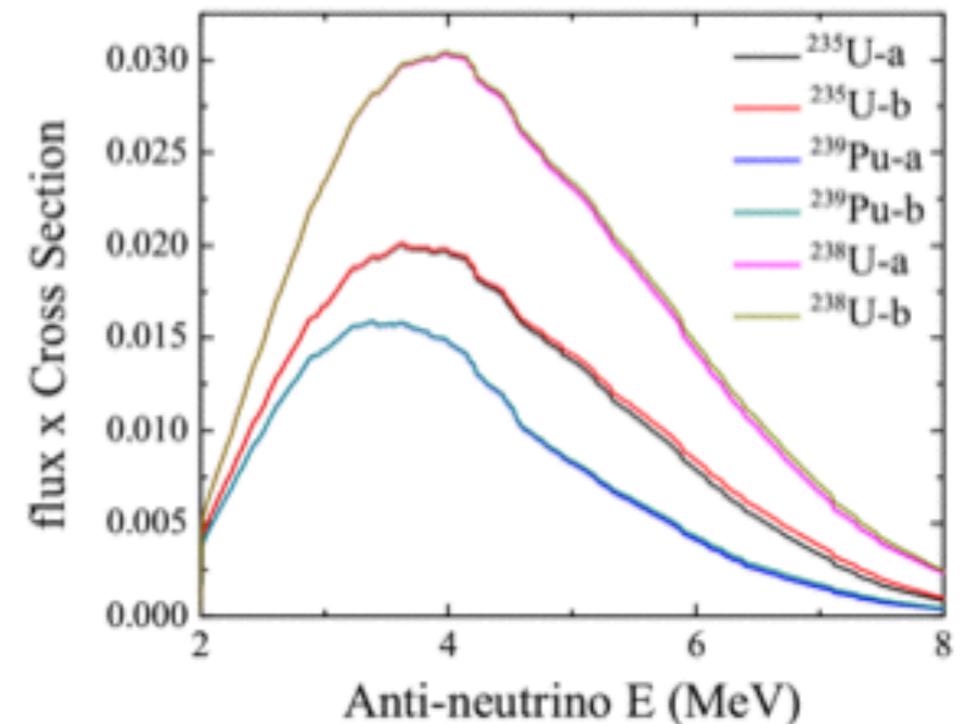
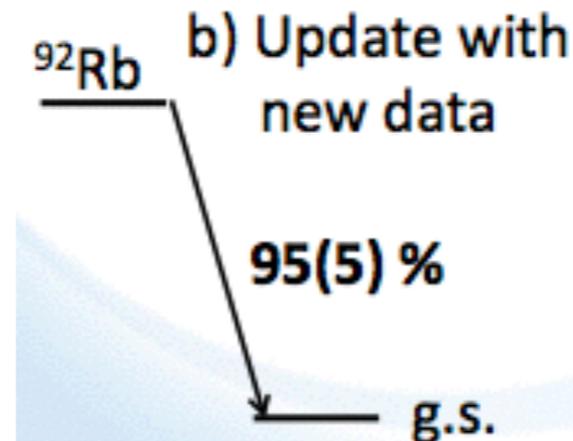
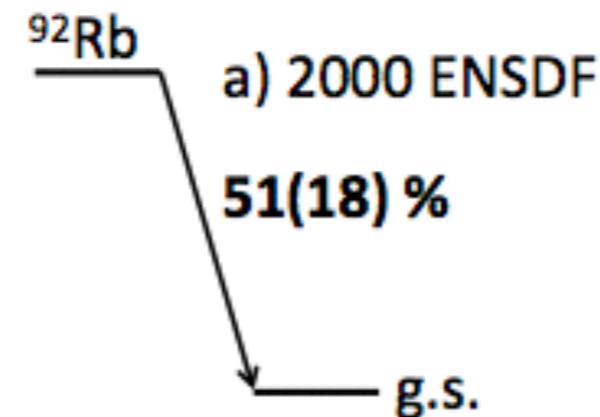
ASSESSMENT OF FISSION PRODUCT  
DECAY DATA FOR DECAY HEAT CALCULATIONS

# Reactor Spectroscopy: Example



- TAGS:  
Total absorption  
gamma  
spectroscopy
- Measure total  
gamma energy,  
not individual  
gamma energies
- Allows ID of  
levels, BRs  
much easier

## One small nucleus, one big effect



A. Sonsogni (BNL), (2010)

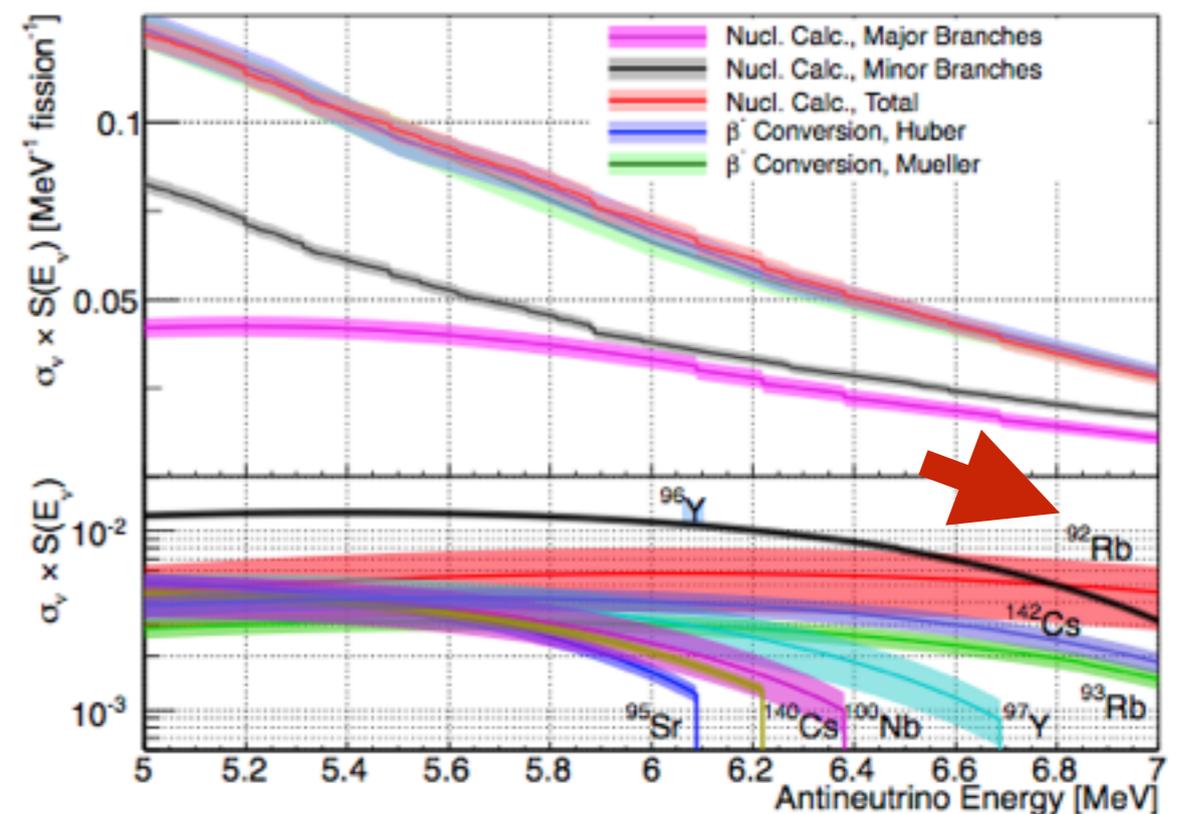
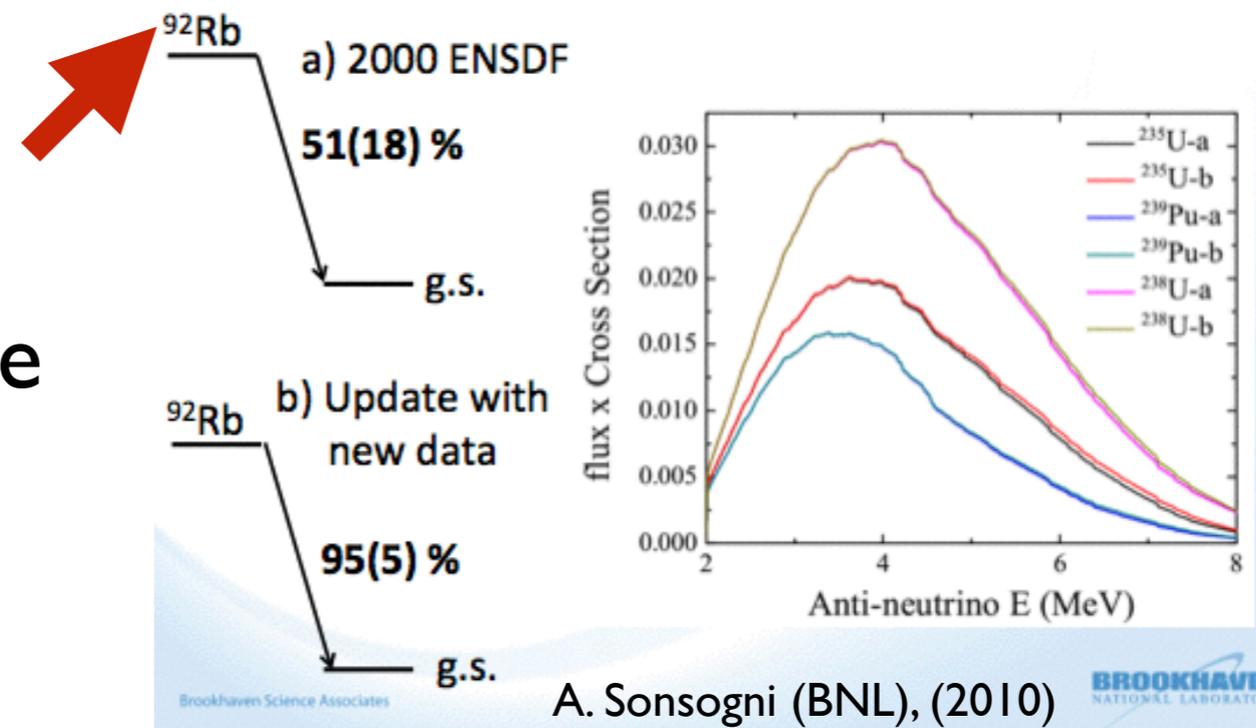
- If branching ratios are known better, decay released in those decays will be modelled better
- Better model = smaller safety factor = \$\$\$ saved.

# Reactor Spectroscopy: Implications



- 5 MeV ‘bump’ region produced by many isotopes of great concern to this decay heat measurement!
- Two anomalies from the same source?
- Reactor spectroscopy measurements can provide:
  - Direct check on existing TAGS measurements
    - TOTALLY different systematics!
  - NEW data if TAGS has not been done!
  - Isotopes: Rb-92, Sr-97, Cs-142

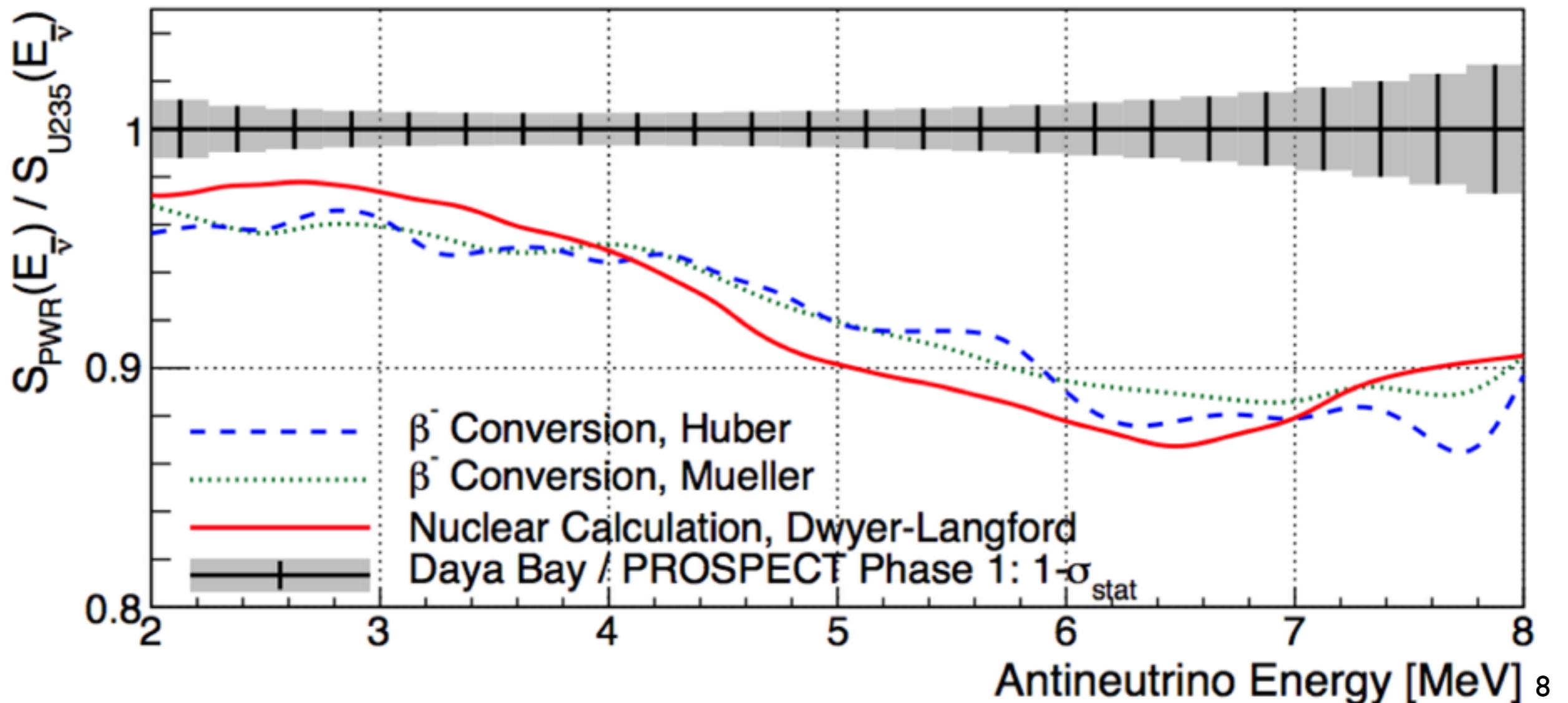
## One small nucleus, one big effect



# Spectrum Measurement HEU:LEU



- HEU-LEU difference, made more explicit:
  - ~10% difference in spectra between low and high energies
  - Extent of this difference depends on exact modeling
    - Ab initio: Predicts larger HEU-LEU spectral variation
    - Larger LEU-HEU variation in spectra: better for non-proliferation!!



# Formulas for Energy Reconstruction



- Daya Bay

- Minimum energy of 1.8 MeV needed to make neutron and positron
- Momentum conservation means positron gets almost all kinetic energy

$$E_{prompt} = E_{\bar{\nu}_e} + (m_n - m_p) + m_{e^-}$$

- MicroBooNE

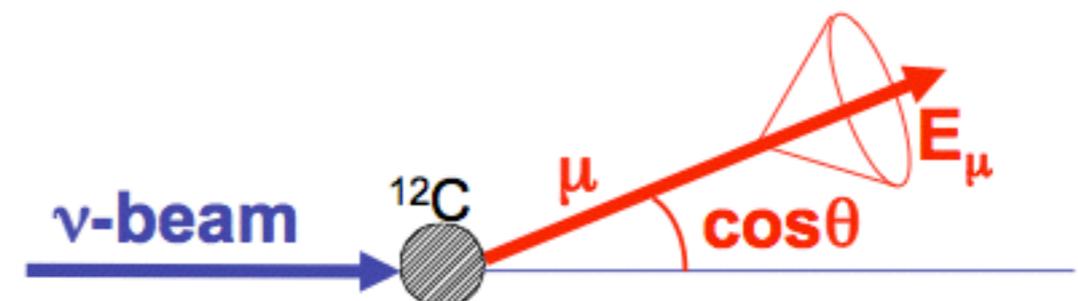
- Not such a simple picture at higher energy; both target and lepton get significant amounts of momentum

- In addition, interacting proton is bound in a nucleus

- Need to measure lepton energy AND angle to get neutrino energy

$$E_{\nu}^{QE} = \frac{2(M - E_B)E_{\mu} - (E_B^2 - 2ME_B + m_{\mu}^2 + \Delta M^2)}{2[(M - E_B) - E_{\mu} + p_{\mu} \cos \theta_{\mu}]}$$

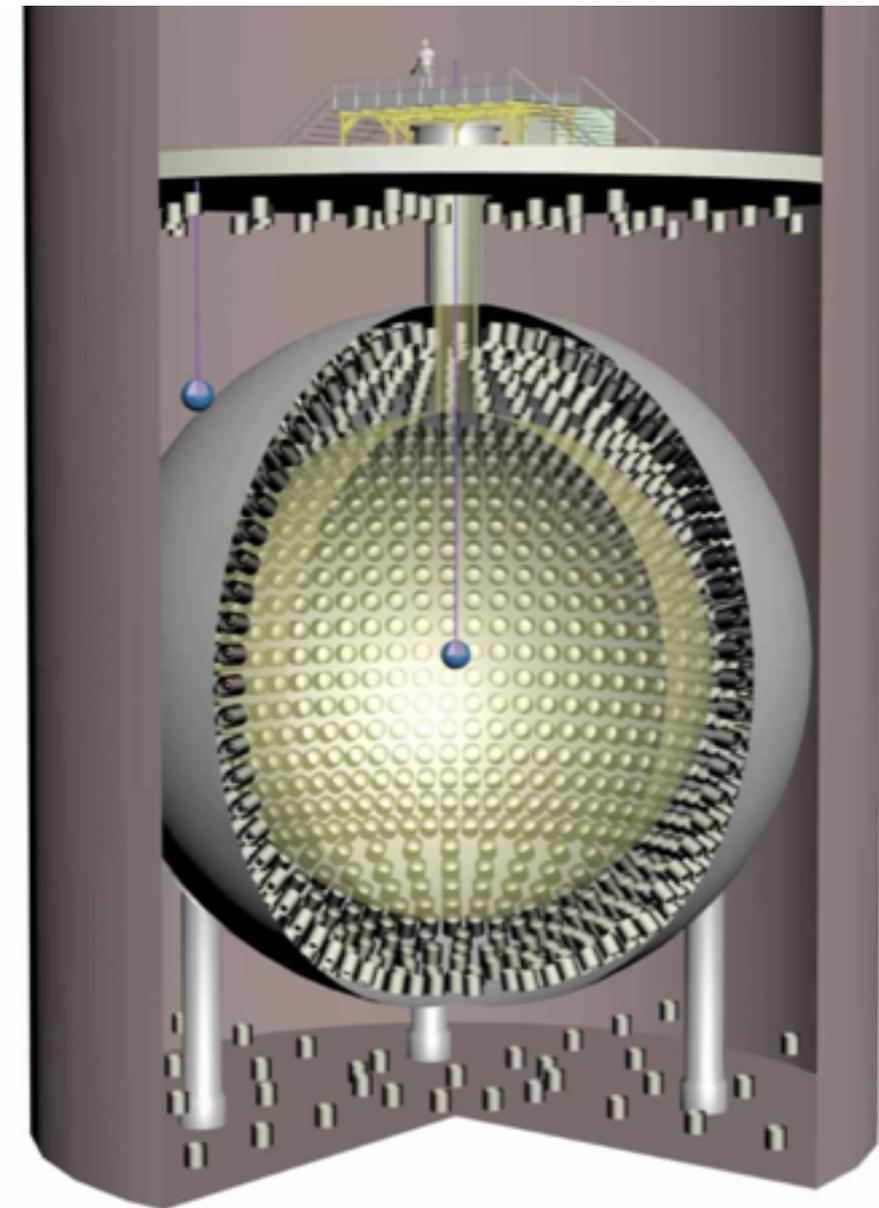
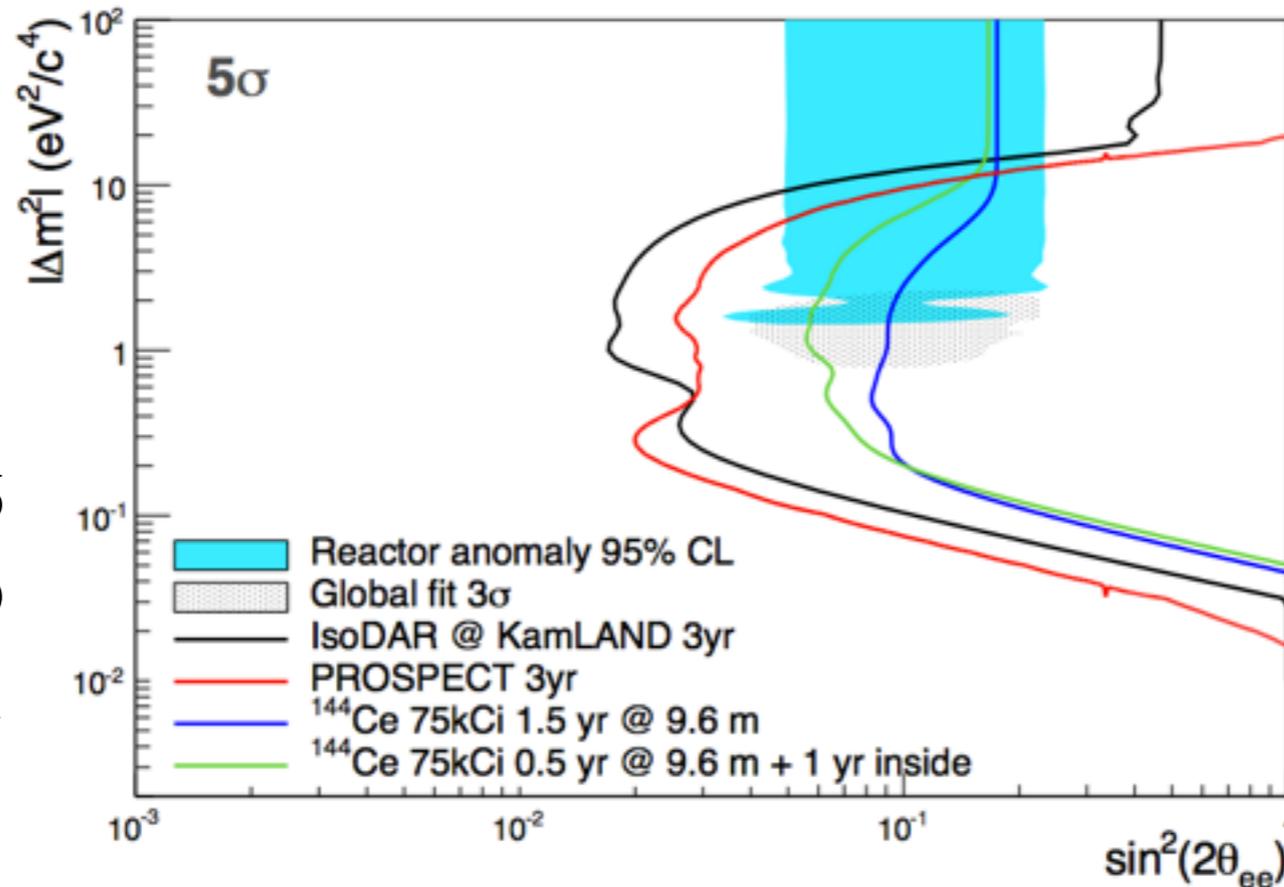
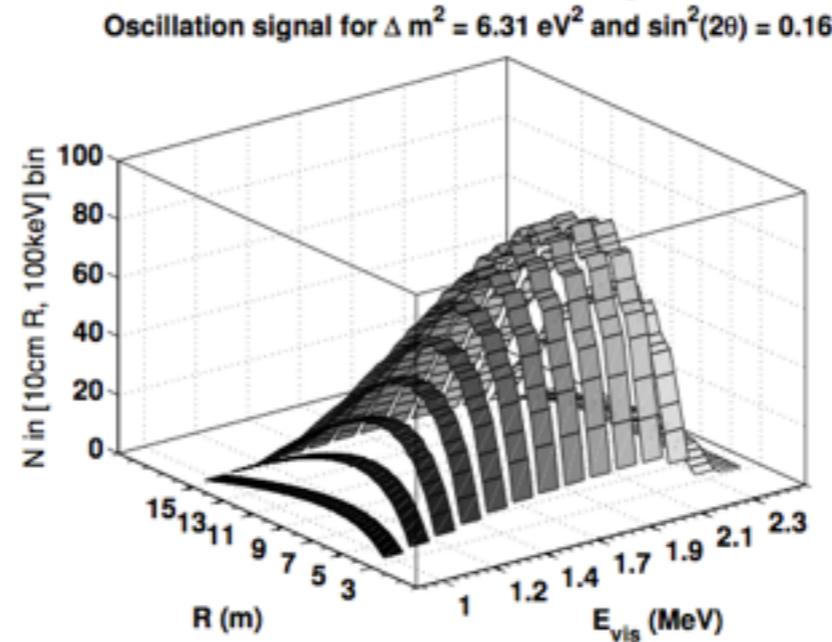
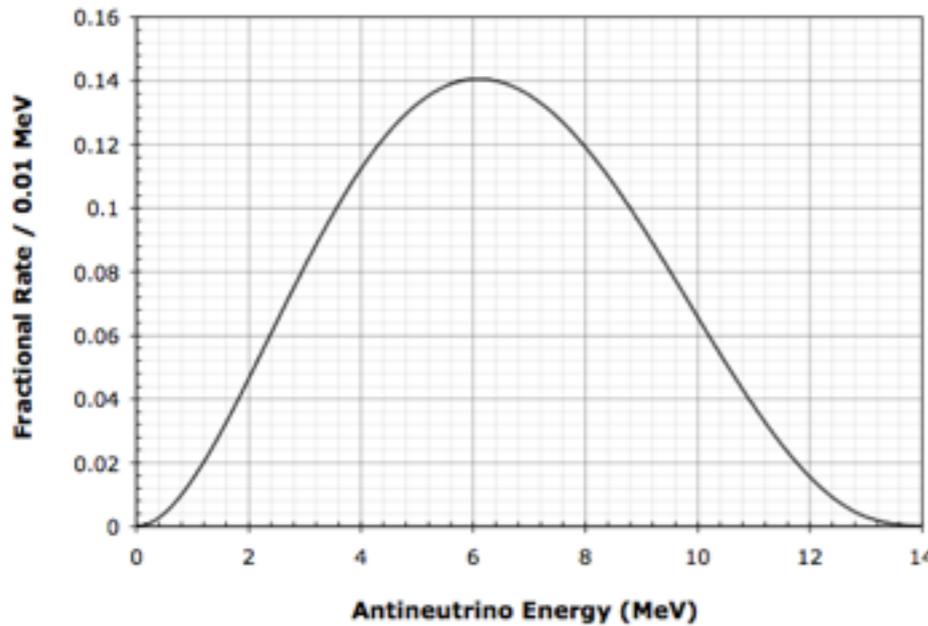
$$Q_{QE}^2 = -m_{\mu}^2 + 2E_{\nu}^{QE}(E_{\mu} - p_{\mu} \cos \theta_{\mu})$$





# Competing Efforts

- CeLAND and SOX: Radioactive source experiments: quick-ish
- IsoDAR: Accelerator-produced beta decay source: longer timescale



arXiv:1312.0896

arXiv:1307.2949

arXiv:1304.7721